Satellite Sounder Observations of Contrasting Tropospheric Moisture Transport Regimes:

Saharan Air Layers, Hadley Cells, and Atmospheric Rivers

Nicholas R. Nalli[1,2], C. D. Barnet[3], T. Reale[2], Q. Liu[2], V. R. Morris[4], J. Ryan Spackman[5], E. Joseph[6], C. Tan[1,2], B. Sun[1,2], F. Tilley[1,2], L. Ruby Leung[7], and D. Wolfe[8]

[1]IMSG, Rockville, Maryland, USA
[2]NOAA/NESDIS/STAR, College Park, Maryland, USA
[3]STC, Columbia, Maryland, USA
[4]Howard University Washington, D.C., USA
[5]STC, NOAA Earth System Research Laboratory, Boulder, CO, USA
[6]SUNY at Albany, Albany, New York, USA
[7]Pacific Northwest National Laboratory, Richland, WA, USA.
[8]Cooperative Institute for Research in Environmental Sciences, Boulder, CO, USA.

2016 NASA Sounder Science Team
Greenbelt, Maryland, USA
September 2016

Acknowledgments

- The **NOAA Joint Polar Satellite System (JPSS-STAR) Office** (L. Zhou, M. D. Goldberg, et al.) and the **NOAA/STAR Satellite Meteorology and Climatology Division** (F. Weng and I. Csiszar).

- **SNPP Sounder EDR Validation Dataset collection**
  - **NOAA AEROSE: V. R. Morris, E. Joseph**, M. Oyola, E. Roper (HU/NCAS); P. J. Minnett, M. Szczodrak, M. Izaguirre (UM/RSMAS); D. Wolfe (NOAA/ESRL); J. W. Smith (STC, NRC)
    - AEROSE works in collaboration with the NOAA PIRATA Northeast Extension (PNE) project (R. Lumpkin, G. Foltz and C. Schmid), and is supported by the NOAA Educational Partnership Program (EPP) grant NA17AE1625, NOAA grant NA17AE1623, JPSS and STAR
  - **CalWater: R. Spackman** (STC); R. Leung (PNNL); C. Fairall, J. Intrieri (NOAA)
  - **ACAPEX:** N. Hickmon, M. Ritsche, A. Haruta, and the ARM Mobile Facility 2 (AMF2); R. Knuteson, J. Gero (UW/CIMSS)

- **SNPP NUCAPS development and validation (past and present)**: A. Gambacorta (STC), F. Iturbide-Sanchez, M. Wilson, K. Zhang, M. Pettey, C. Brown, A. K. Sharma, (STAR); R. O. Knuteson (UW/CIMSS)

Outline

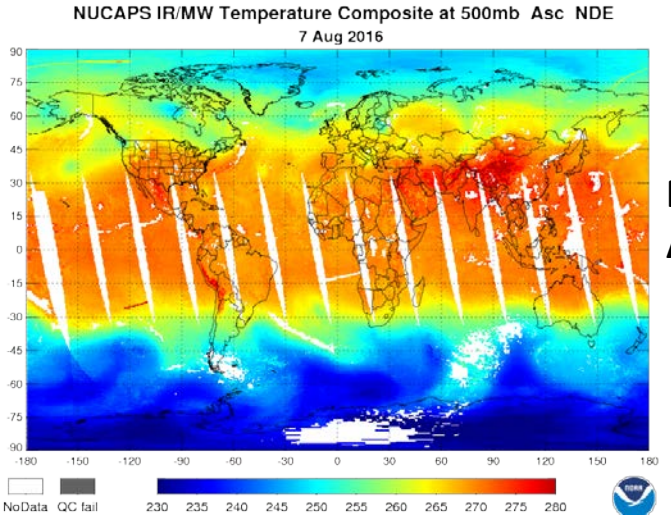
- **Intro: Sounding Datasets**
  - Satellite Sounder Data: NUCAPS Algorithm
  - Truth Data: Dedicated RAOBs
- **Dry Transport: Saharan Air Layers and Hadley Cells**
  - **2013 NOAA Aerosols and Ocean Science Expedition (AEROSE)**
    - Statistical analysis – NUCAPS versus RAOB
    - Spatial cross-sectional analyses – NUCAPS versus RAOB
- **Moist Transport: Atmospheric Rivers**
  - **2015 CalWater/ACAPEX**
    - Statistical analysis – NUCAPS versus RAOB
    - Temporal cross-sectional analyses – RAOB versus NUCAPS
- **Summary and Discussion**

Satellite Sounder Observations of Contrasting Tropospheric Moisture Transport Regimes

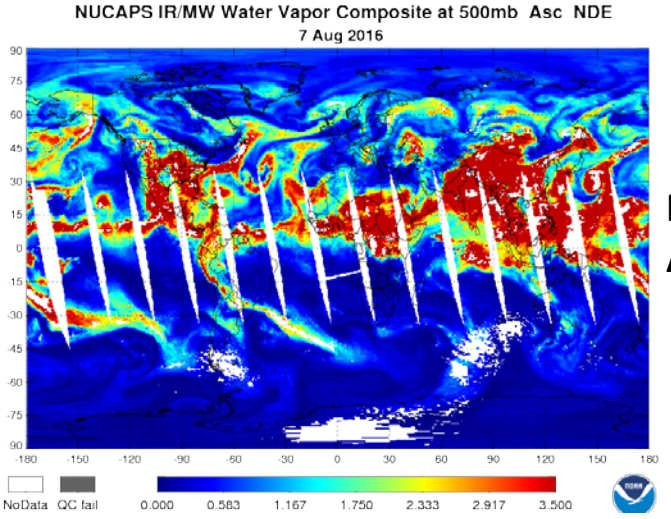
INTRO: SOUNDING DATASETS

Satellite Sounder Data: NOAA Unique Combined Atmospheric Processing System (NUCAPS) Algorithm

- **Operational algorithm**
  - Unified Sounder Science Team (AIRS/IASI/CrIS) retrieval algorithm (*Susskind, Barnet and Blaisdell,* IEEE 2003; *Gambacorta et al.,* 2014)
  - Global non-precipitating conditions
  - Atmospheric Vertical Temperature , Moisture Profiles (**AVTP**, **AVMP**)
  - Trace gases (O_3, CO, CO_2, CH_4)
    - See **Session 4: Atmospheric Composition** presentation on Thursday
  - Validated Maturity for AVTP/AVMP, Sep 2014
- **Users**
  - **Weather Forecast Offices (AWIPS)**
    - Nowcasting / severe weather
    - Alaska (cold core)
  - NOAA/CPC (OLR)
  - NOAA/ARL (IR ozone, trace gases)
  - TOAST (IR ozone)
  - Basic and applied science research (e.g., *Pagano et al.,* 2014)
    - Via NOAA Data Centers (e.g., CLASS)
    - Universities, peer-reviewed pubs



NUCAPS AVTP



NUCAPS AVMP

Long Term Monitoring

http://www.star.nesdis.noaa.gov/jpss/EDRs/products_Soundings.php

http://www.ospo.noaa.gov/Products/atmosphere/soundings/nucaps/index.html

Truth Data: Ship-Based Dedicated Radiosonde Observations (RAOBS)

- **Vaisala RS92** GPS rawinsondes
  - Pressure, temperature, humidity
  - GPS winds and altitude, $z(t)$
- **JPSS Funded**
  - Launched coinciding with LEO environmental satellite overpasses
    - Suomi NPP (CrIS/ATMS)
    - MetOp-A and -B (IASI)
    - Aqua, A-Train (AIRS)
  - **Not** uploaded into GTS (i.e., **not assimilated**), truly independent
  - **SNPP-dedicated** launches
    - **66 during CalWater/ACAPEX campaign** (Jan-Feb 2015)
    - **69 during AEROSE 2013a campaign** (Jan-Feb 2013)

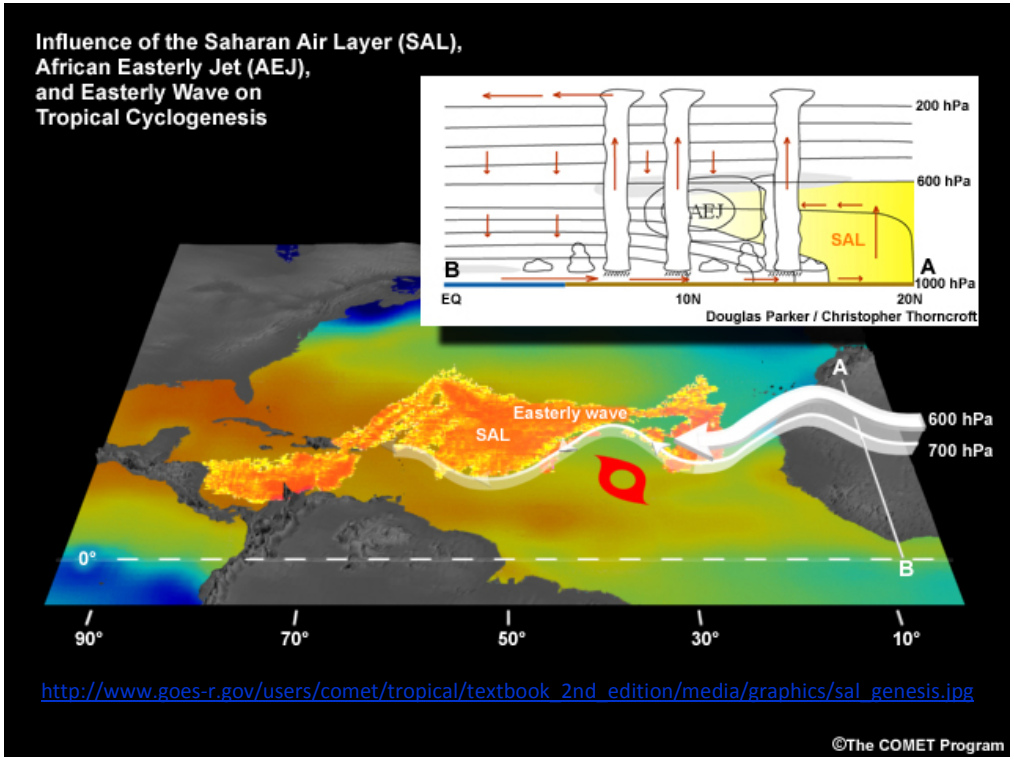
Satellite Sounder Observations of Contrasting Tropospheric Moisture Transport Regimes

DRY TRANSPORT: SAHARAN AIR LAYERS AND HADLEY CELLS

Saharan Air Layers and Hadley Cells

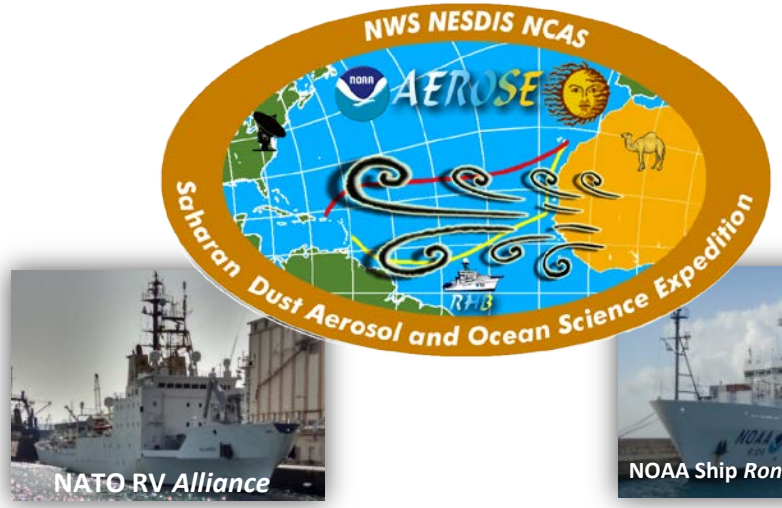
- **Saharan Air Layers (SAL)**
  - Synoptic to mesoscale **stable layers of dry, warm air of desert origin**
  - **Advect across the Atlantic Ocean**, often accompanying high levels of Saharan dust aerosols (*Carlson and Prospero* 1972).
  - These **stabilizing conditions** may **suppress hurricane activity** over the Atlantic (e.g., *Karyampudi and Pierce* 2002; *Dunion and Velden* 2004; *Wong and Dessler* 2005; *Evan et al.* 2006; *Sun et al.* 2008; *Shu and Wu* 2009), and may also be self-sustaining as a result of reduced radiative cooling in the layer

- **Hadley Cells**
  - **Global/synoptic scale circulation cells** consisting of uplift along the ITCZ axis and associated poleward divergence aloft
  - **Subtropical subsidence** causes drying and warming, leading to deep columns of dry air with stabilizing tropospheric inversions at their bases ("advection–condensation model"; *Pierrehumbert et al.* 2007)

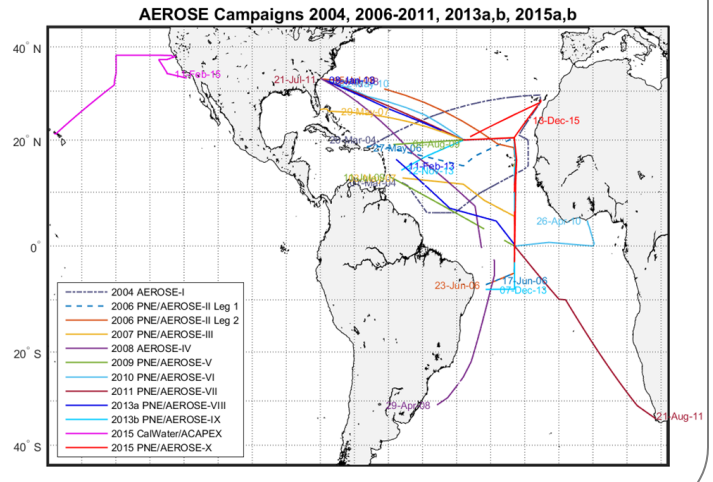


NOAA Aerosols and Ocean Science Expedition (AEROSE)

- **Collaborative, multidisciplinary ship-based intensive field campaigns** focused on aerosol chemistry and transport (*Morris et al.* 2006; *Nalli et al.* 2011)
  - **AEROSE domain** is of interest to satellite sounder cal/val, and mesoscale-synoptic observing missions
    - Satellite data over oceans have the biggest impact on NWP
    - Ocean surfaces are easier to characterize radiatively
    - SALs, Saharan dust, biomass burning
  - **Trans-Atlantic campaigns** completed **since the launch of SNPP**
    - **PNE/AEROSE-8** (NOAA Ship *Ronald H. Brown*, Jan-Feb 2013; 38 days)
    - PNE/AEROSE-9 (NOAA Ship *Ronald H. Brown*, Nov-Dec 2013; 30 days)
    - PNE/AEROSE-X (NATO RV *Alliance*, Nov-Dec 2015; 30 days)

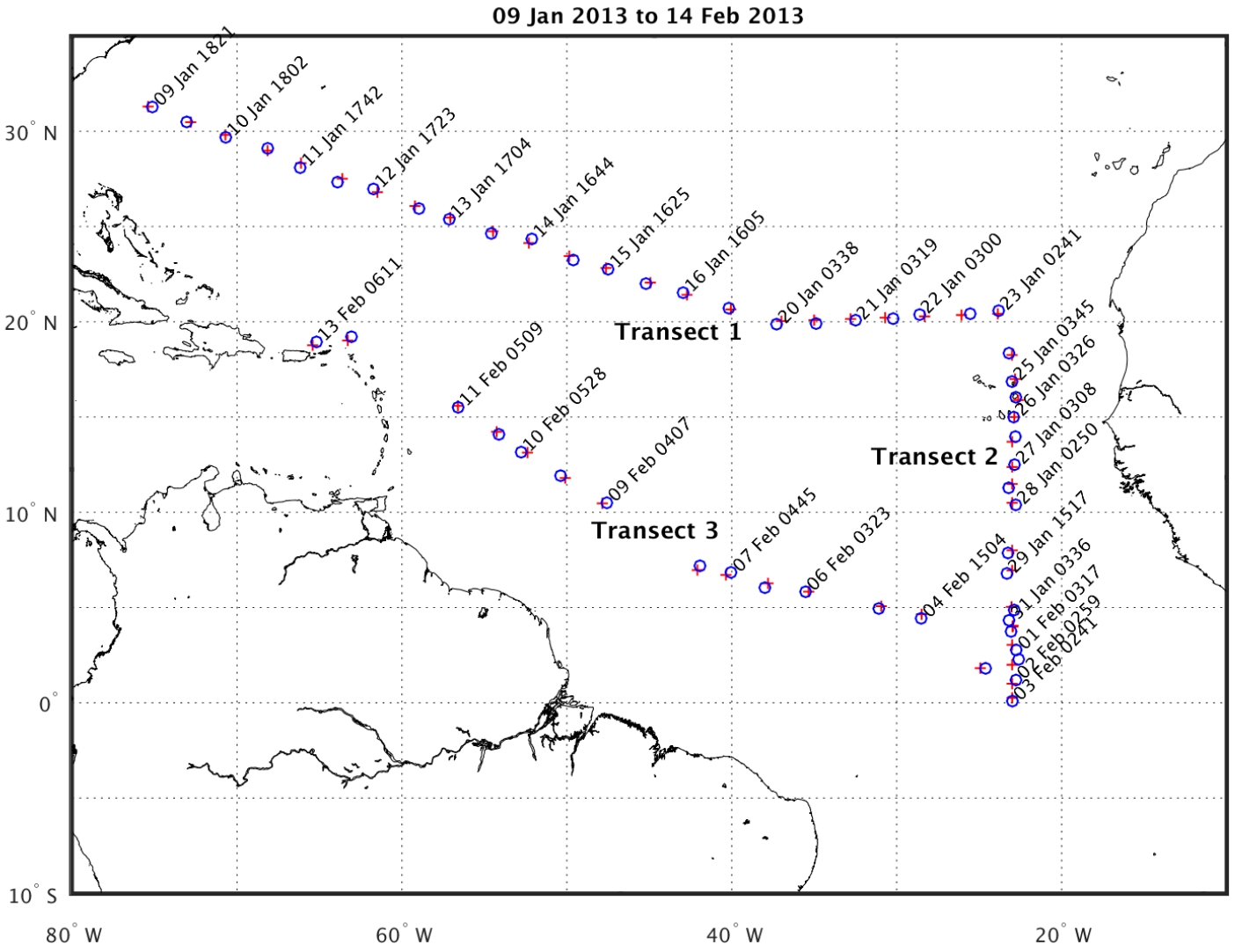


AEROSE Cruise Tracks – "Spaghetti Plot"



2013 AEROSE Radiosonde Launches (Jan-Feb 2013)

+ RAOB launch
o nearest FOR

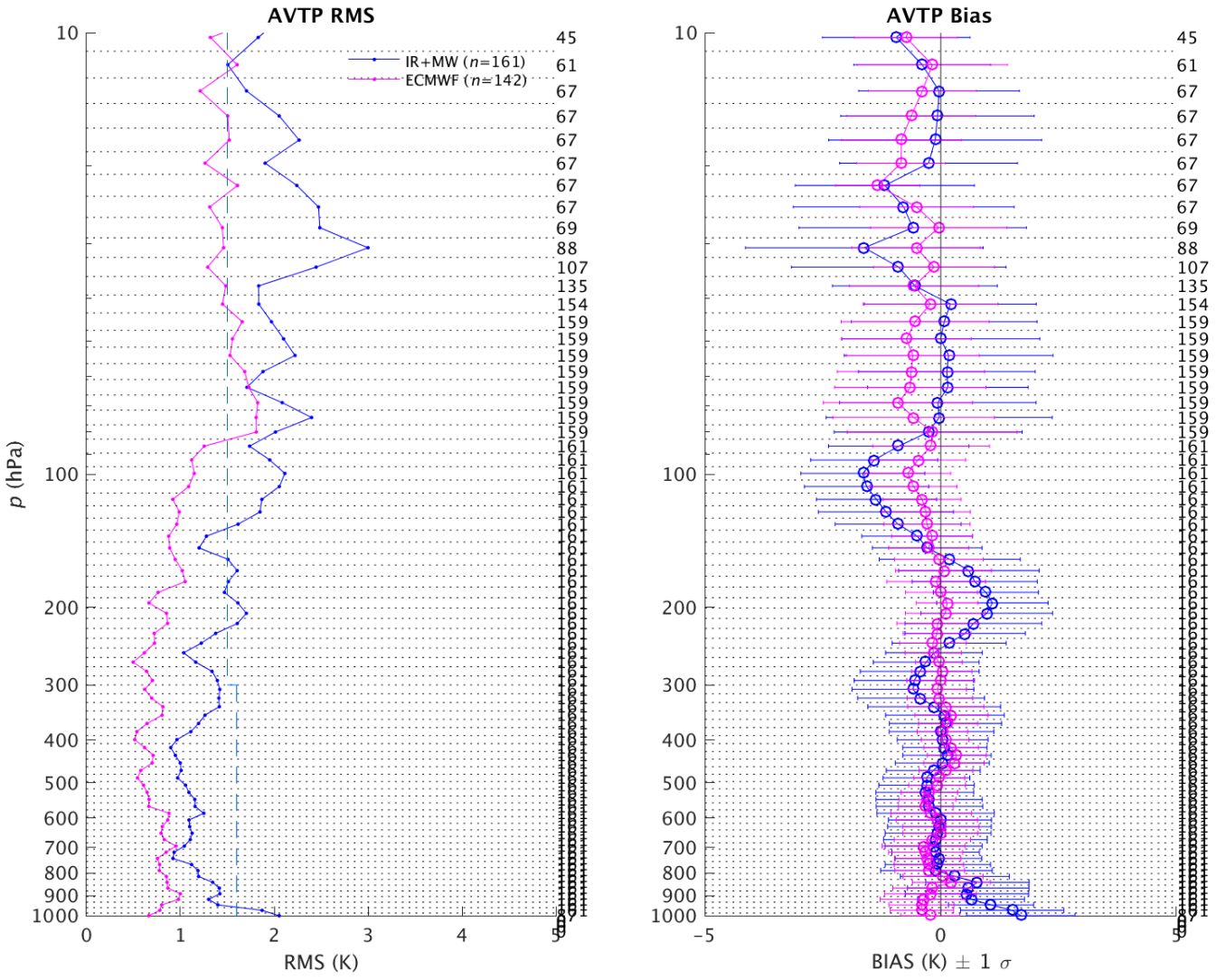


AVTP Statistical Summary (Accepted Cases)

2013 AEROSE RAOBs, 100 RTA Layers

Accepted FOR within 75 km radius

Launches 0–70 min prior to overpasses

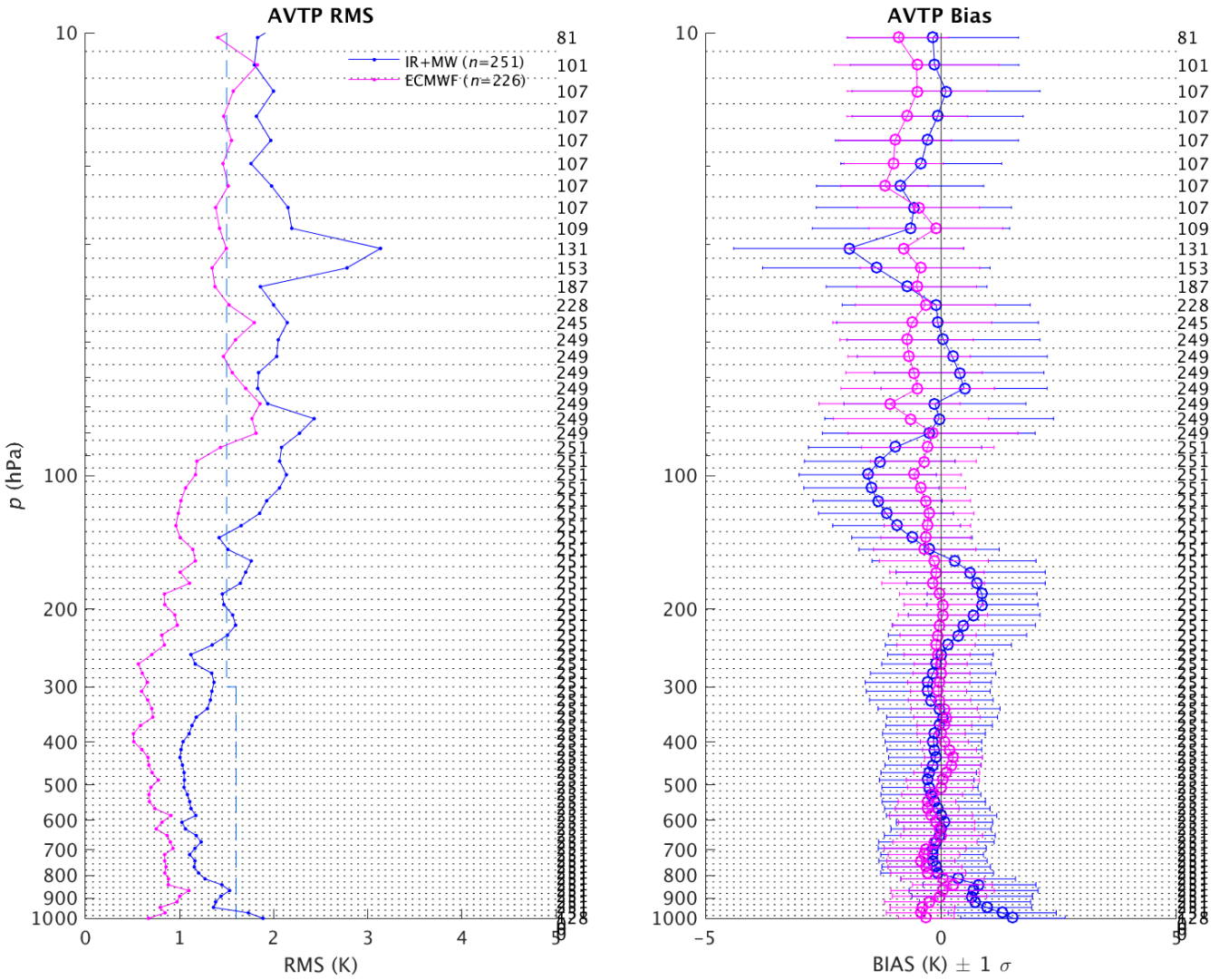


AVTP Statistical Summary (All Cases)

2013 AEROSE RAOBs, 100 RTA Layers

All FOR within 75 km radius

Launches 0–70 min prior to overpasses

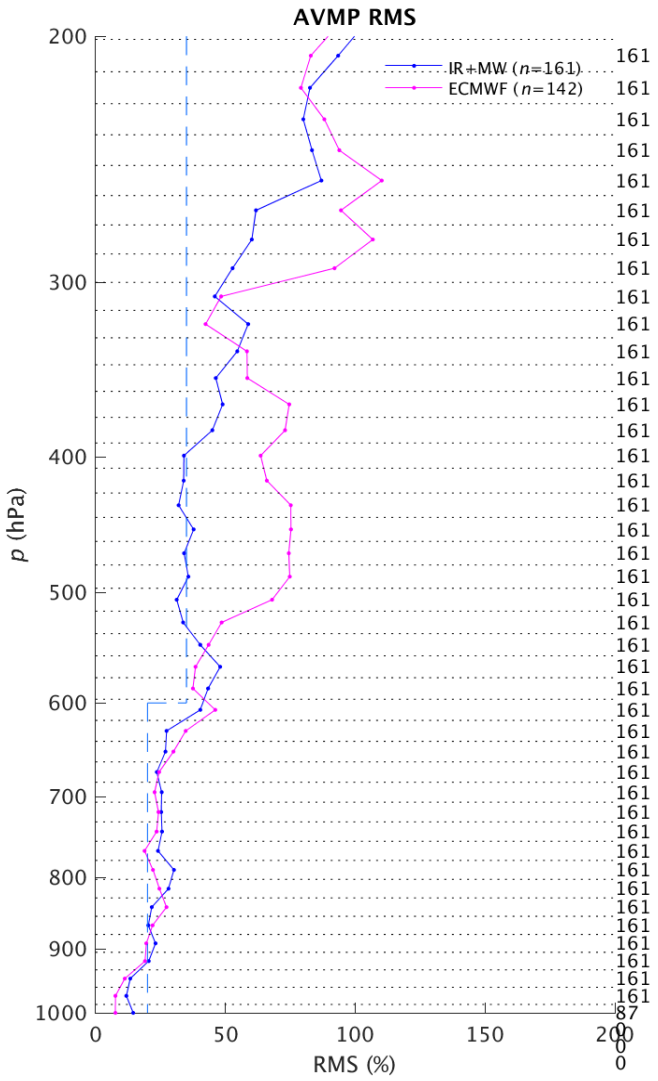


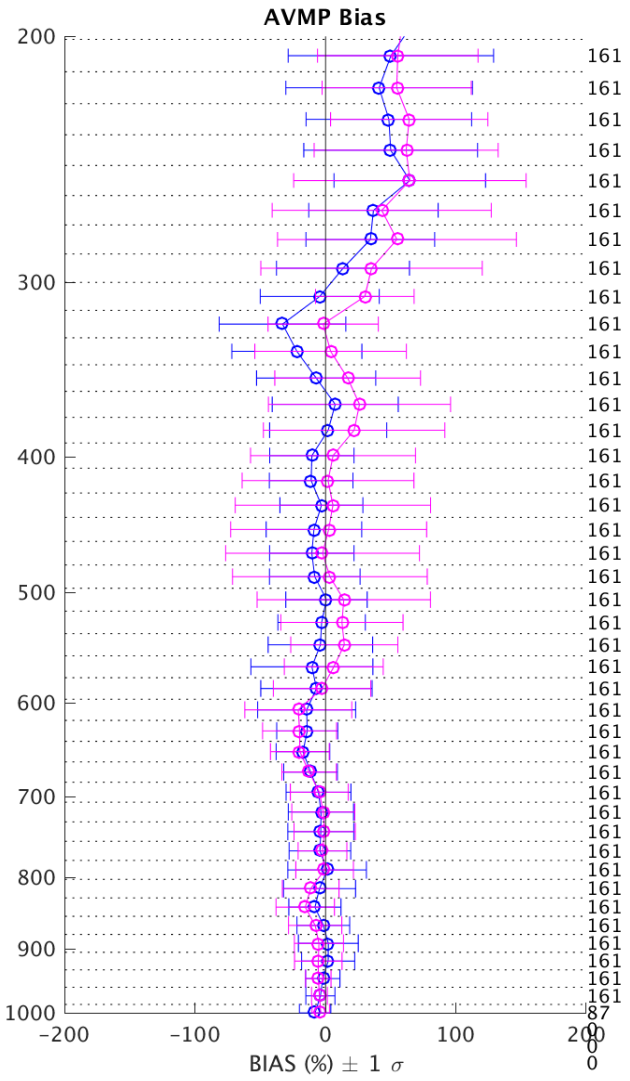
AVMP Statistical Summary (Accepted Cases)

2013 AEROSE RAOBs, 100 RTA Layers

Accepted FOR within 75 km radius

Launches 0–70 min prior to overpasses



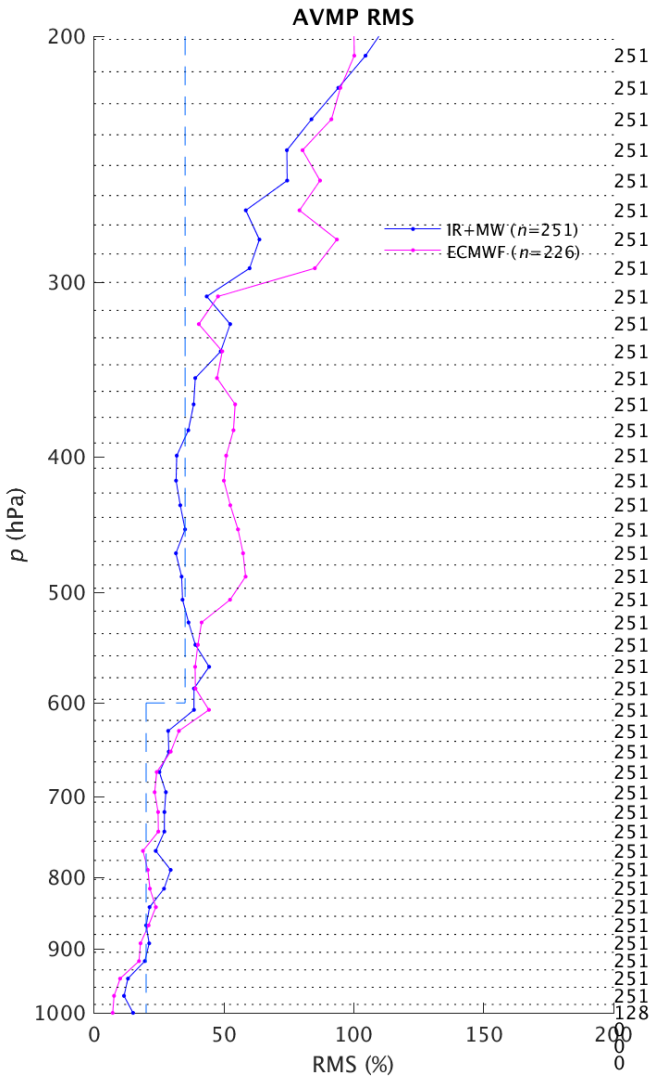


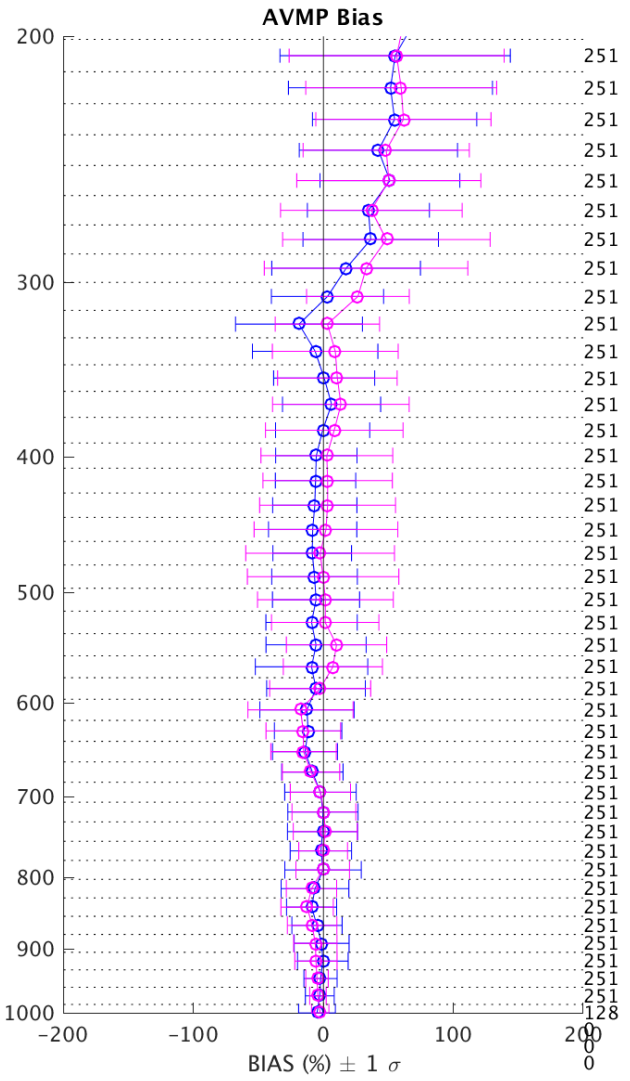
AVMP Statistical Summary (All Cases)

2013 AEROSE RAOBs, 100 RTA Layers

All FOR within 75 km radius

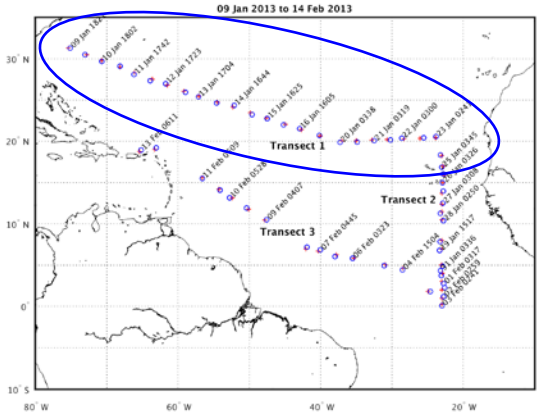
Launches 0–70 min prior to overpasses

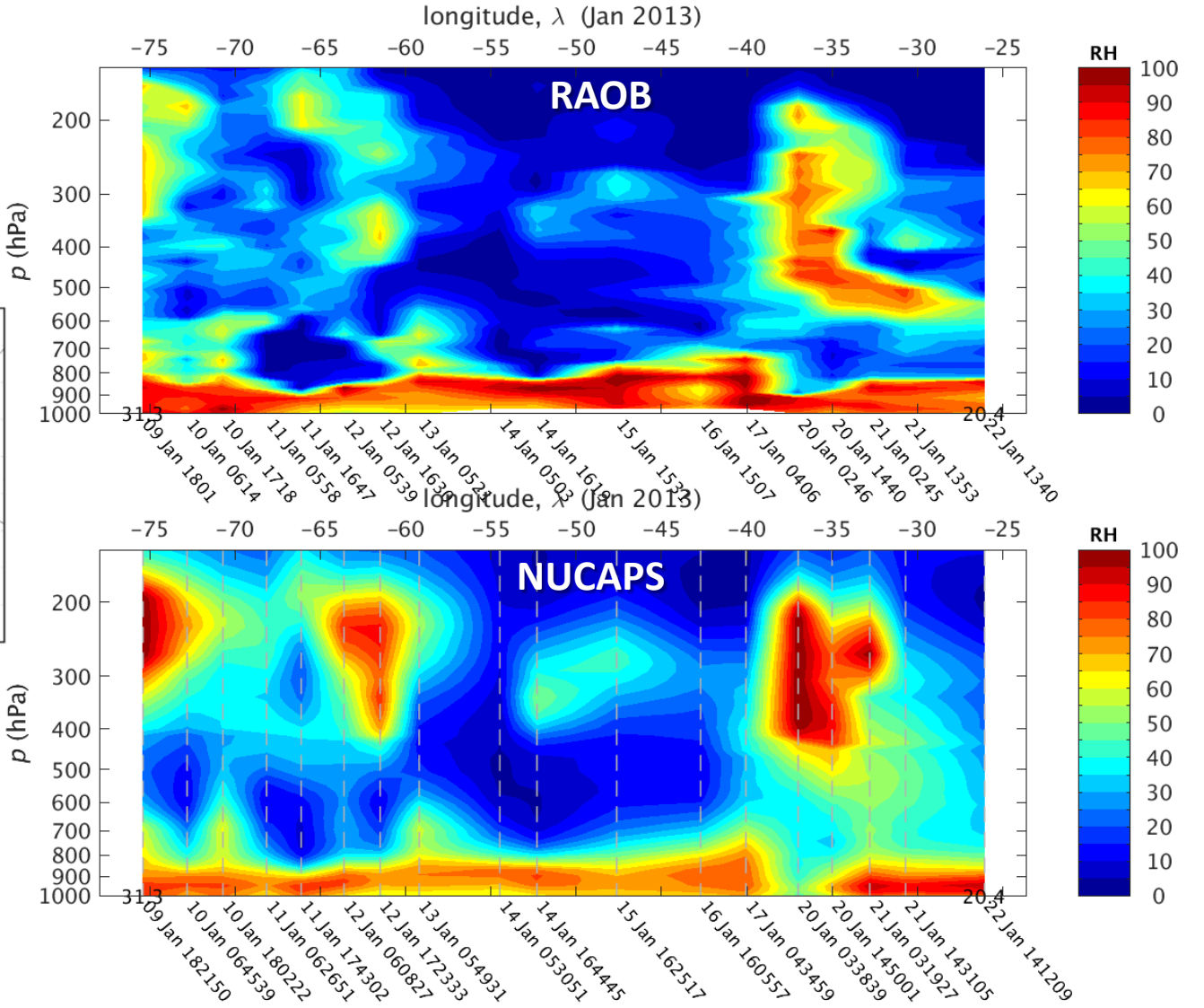




Zonal RH Cross-Section (Accepted Cases)

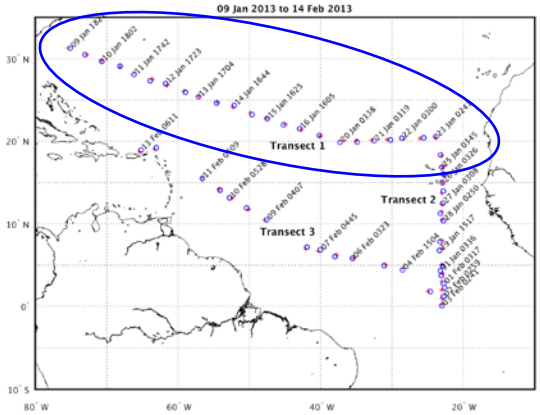
2013 AEROSE NW-SE Transect 1

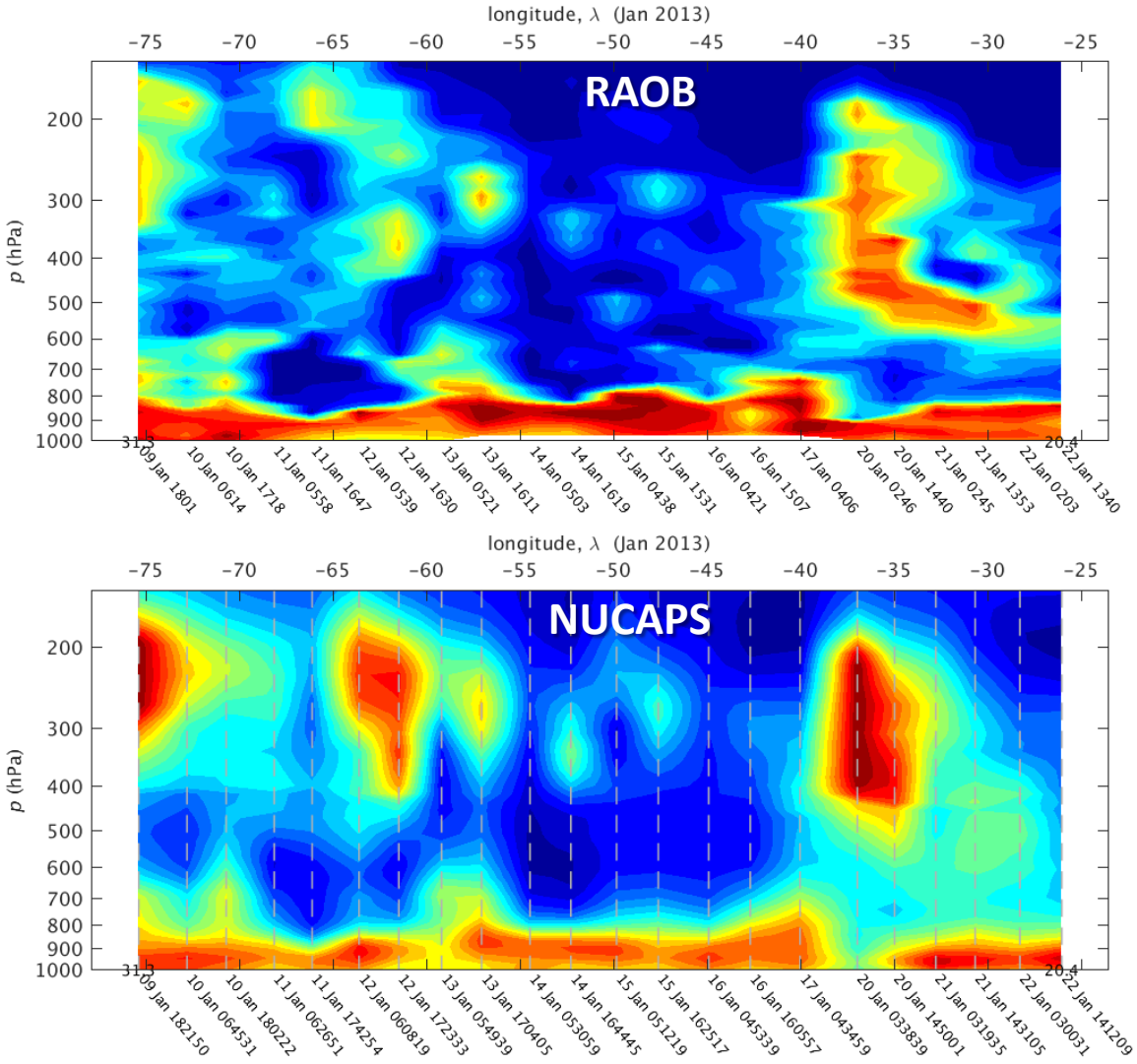




Zonal RH Cross-Section (All Cases)

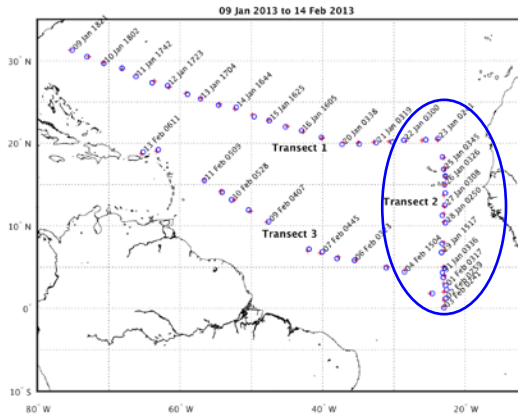
2013 AEROSE NW-SE Transect 1

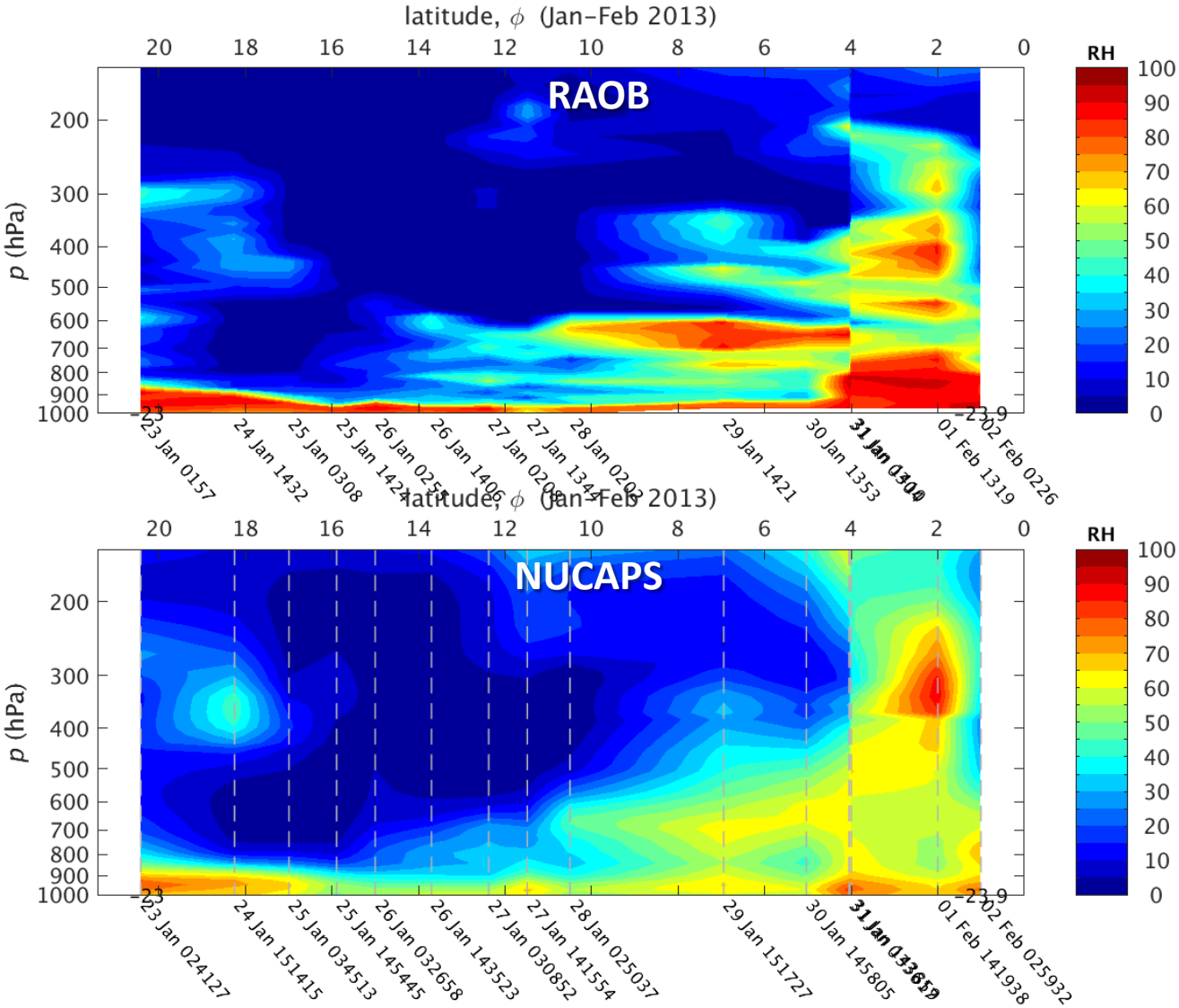




Meridional RH Cross-Section (Accepted Cases)

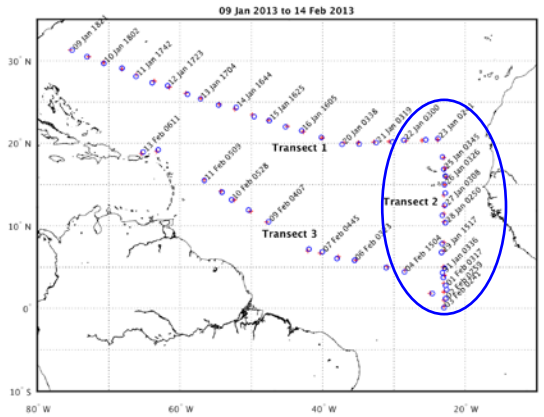
2013 AEROSE N-S Transect 2

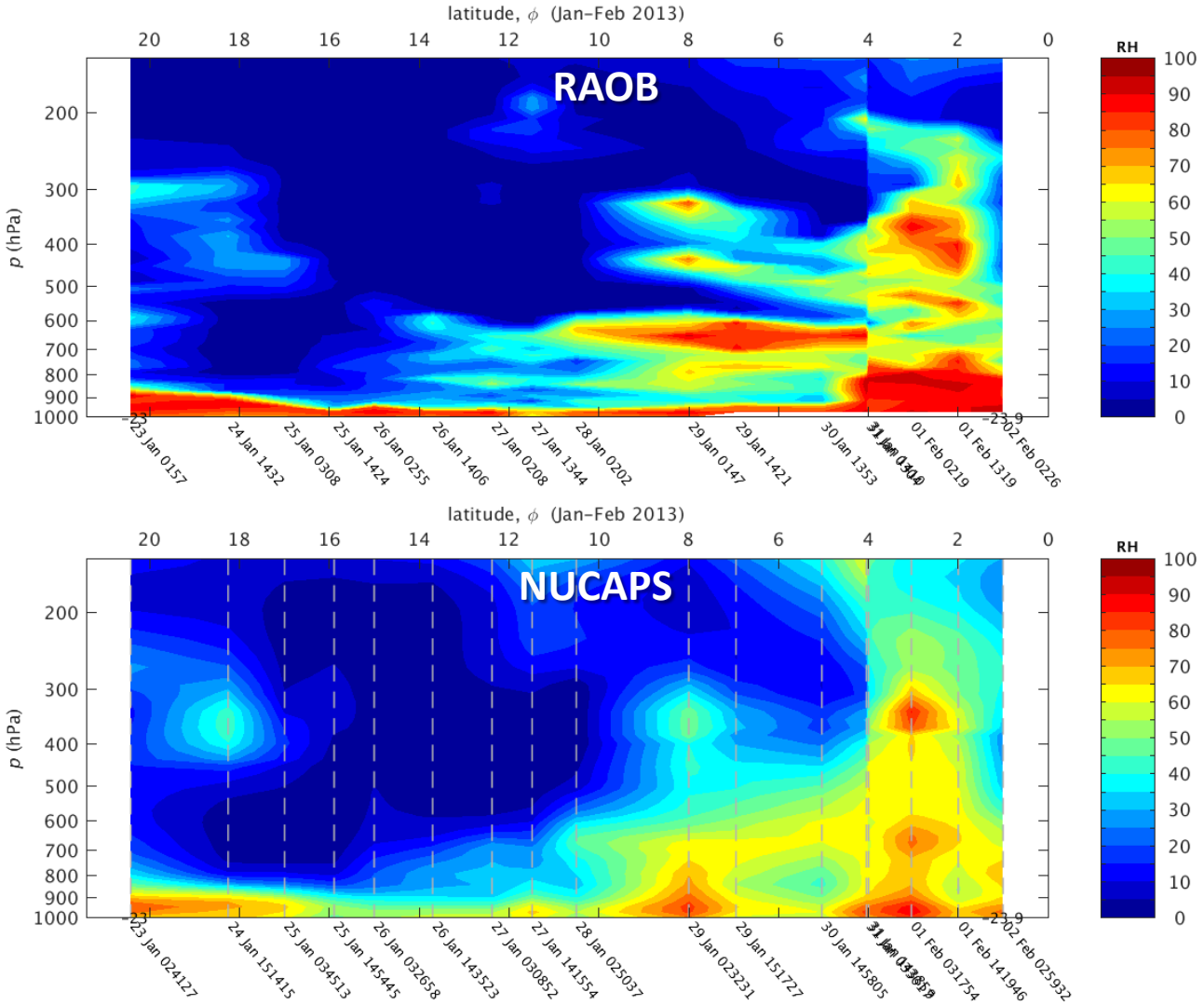




Meridional RH Cross-Section (All Cases)

2013 AEROSE N-S Transect 2





Satellite Sounder Observations of Contrasting Tropospheric Moisture Transport Regimes

MOIST TRANSPORT: ATMOSPHERIC RIVERS

Eastern Pacific Ocean "Atmospheric Rivers"

- **Atmospheric Rivers (ARs)** are narrow conveyor belts of water vapor that extend thousands of km, delivering most of the moisture associated with landfalling storms from the Pacific Ocean

- Understanding of ARs is important for **forecasting West Coast precipitation**, and given **California droughts** of recent years, ARs are a hot topic of current research

Figure from CalWater2 whitepaper (courtesy of Ryan Spackman, STC)

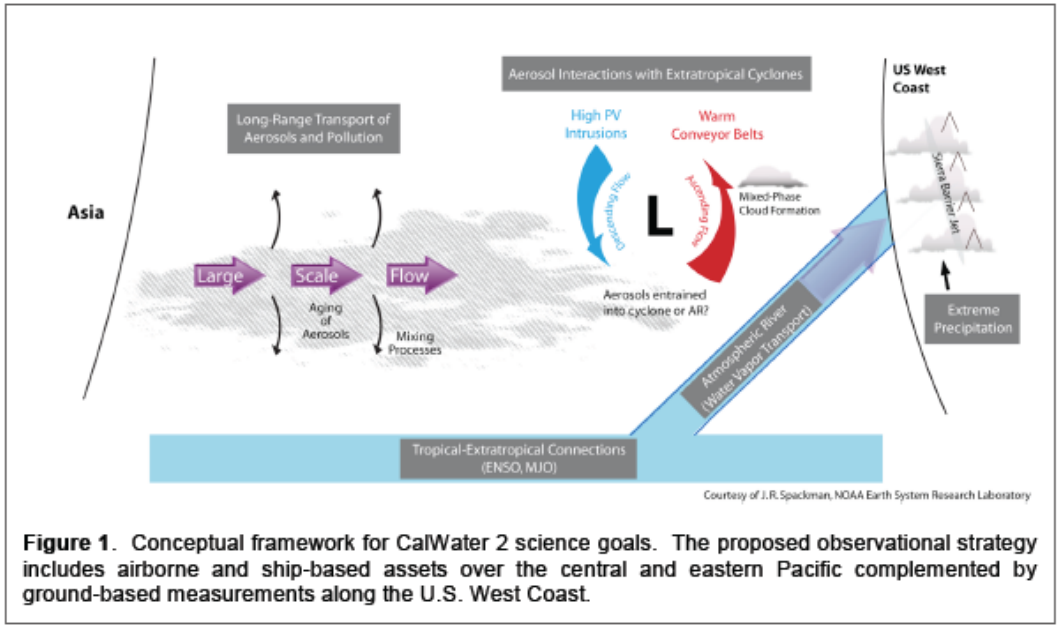


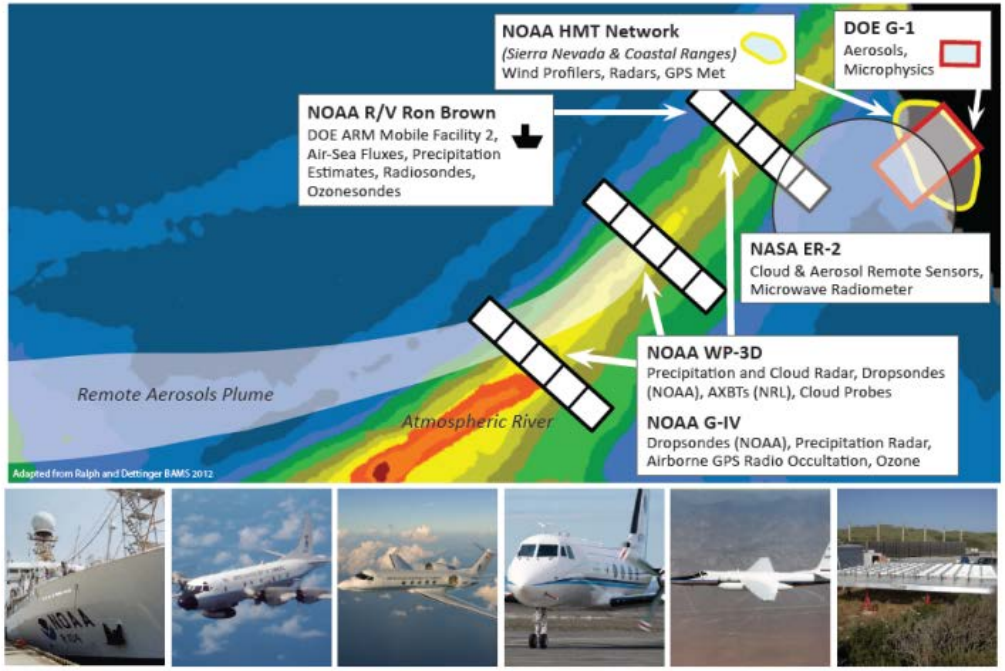
Figure 1. Conceptual framework for CalWater 2 science goals. The proposed observational strategy includes airborne and ship-based assets over the central and eastern Pacific complemented by ground-based measurements along the U.S. West Coast.

2015 CalWater/ACAPEX

- **California's water (CalWater)** is influenced by extreme precipitation events associated with
  - **Atmospheric Rivers (ARs)**
  - **Aerosols** from local and remote sources

- **CalWater 2015** was a multi-institutional intensive field campaign to obtain a suite of observations for gaining understanding of these phenomena
  - Aircraft-based data
    - NOAA P-3
    - NOAA G-IV
    - DOE G-1
    - NASA ER-2
  - Land-based networks
    - NOAA Hydrometeorology Testbed (HMT) mesonet sites
  - **ACAPEX/AEROSE** sub-campaign, NOAA *Ronald H. Brown,* AMF2
    - Leg 1: Honolulu to San Francisco
    - Leg 2: San Francisco to San Diego

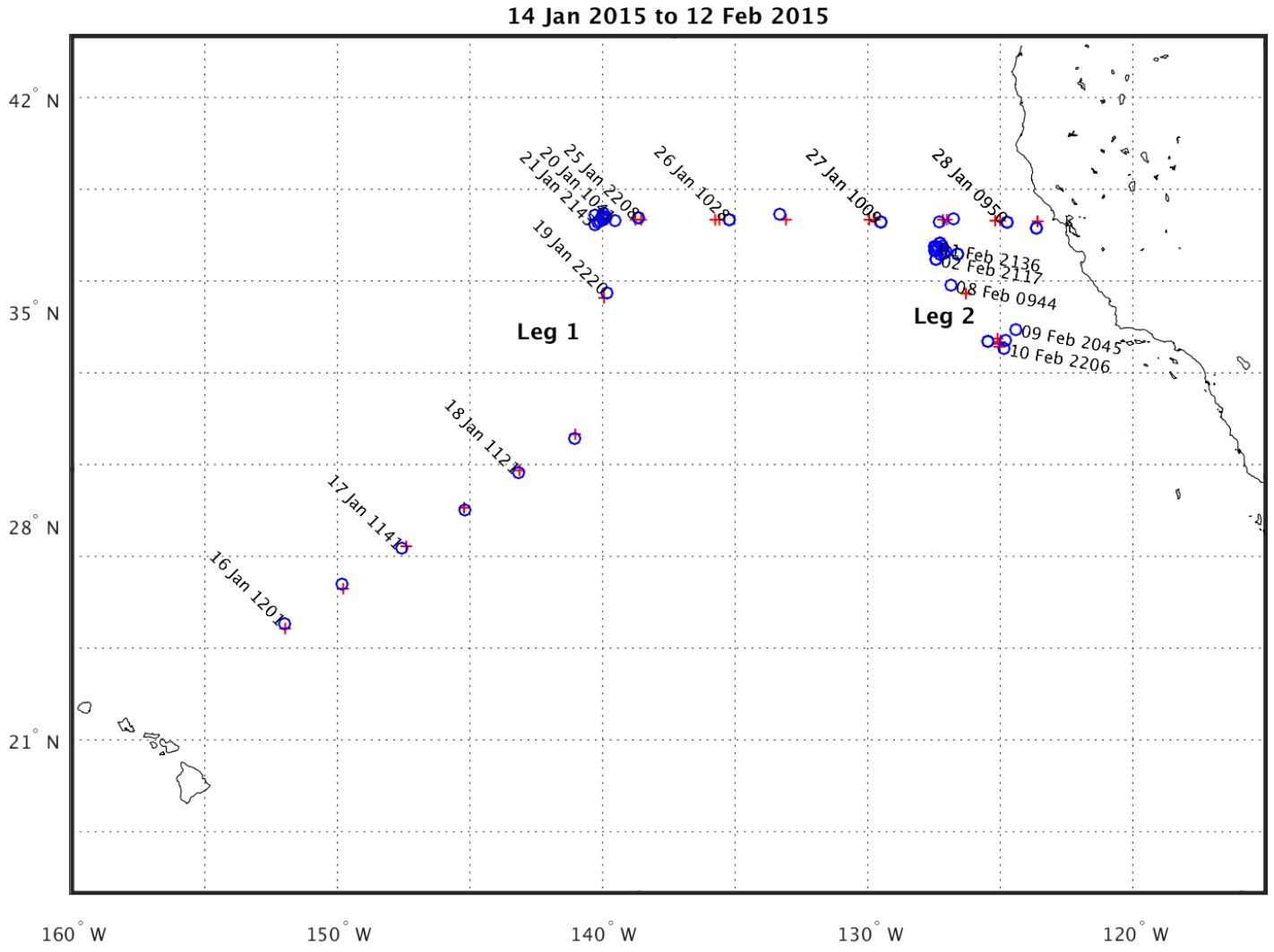
Figure from CalWater2 whitepaper (courtesy of Ryan Spackman, STC)



ACAPEX photos courtesy of Jon Gero (UW/CIMSS)

2015 CalWater/ACAPEX Radiosonde Launches
(Jan-Feb 2015)

+ RAOB launch
o nearest FOR

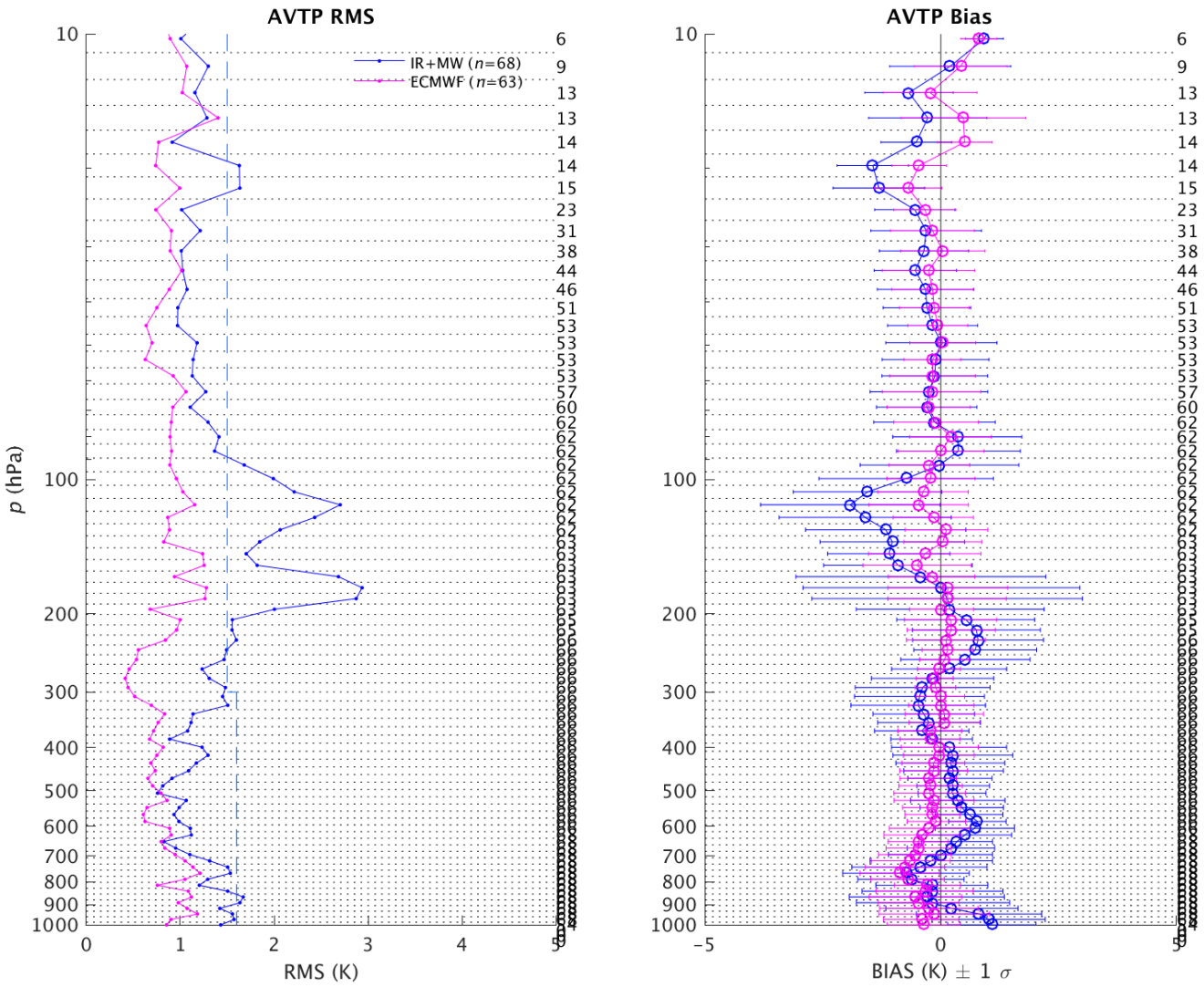


AVTP Statistical Summary (Accepted Cases)

2015 CalWater/ACAPEX RAOBs, 100 RTA Layers

Accepted FOR within 50 km radius

Launches 0–70 min prior to overpasses

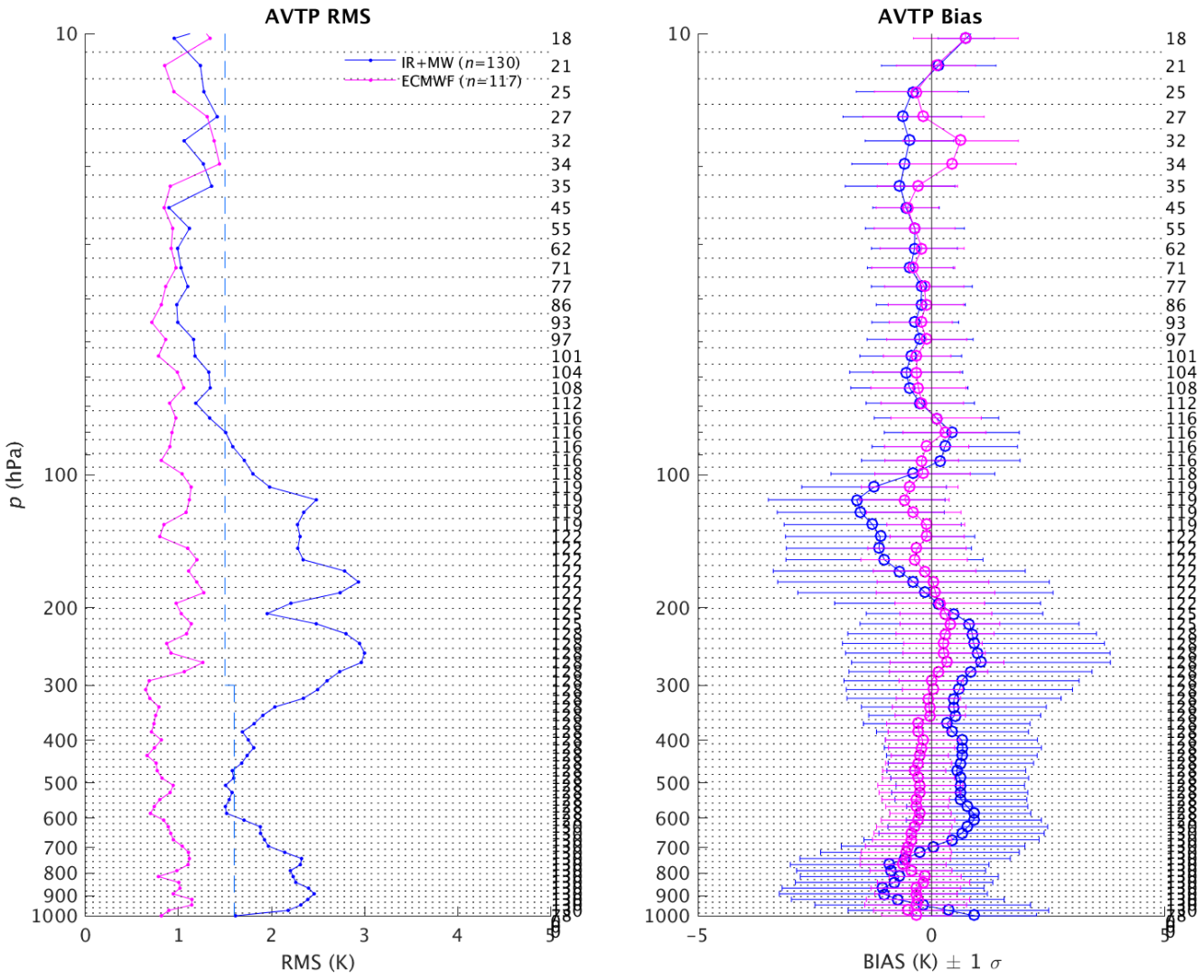


AVTP Statistical Summary (All Cases)

2015 CalWater/ACAPEX RAOBs, 100 RTA Layers

All FOR within 50 km radius

Launches 0–70 min prior to overpasses

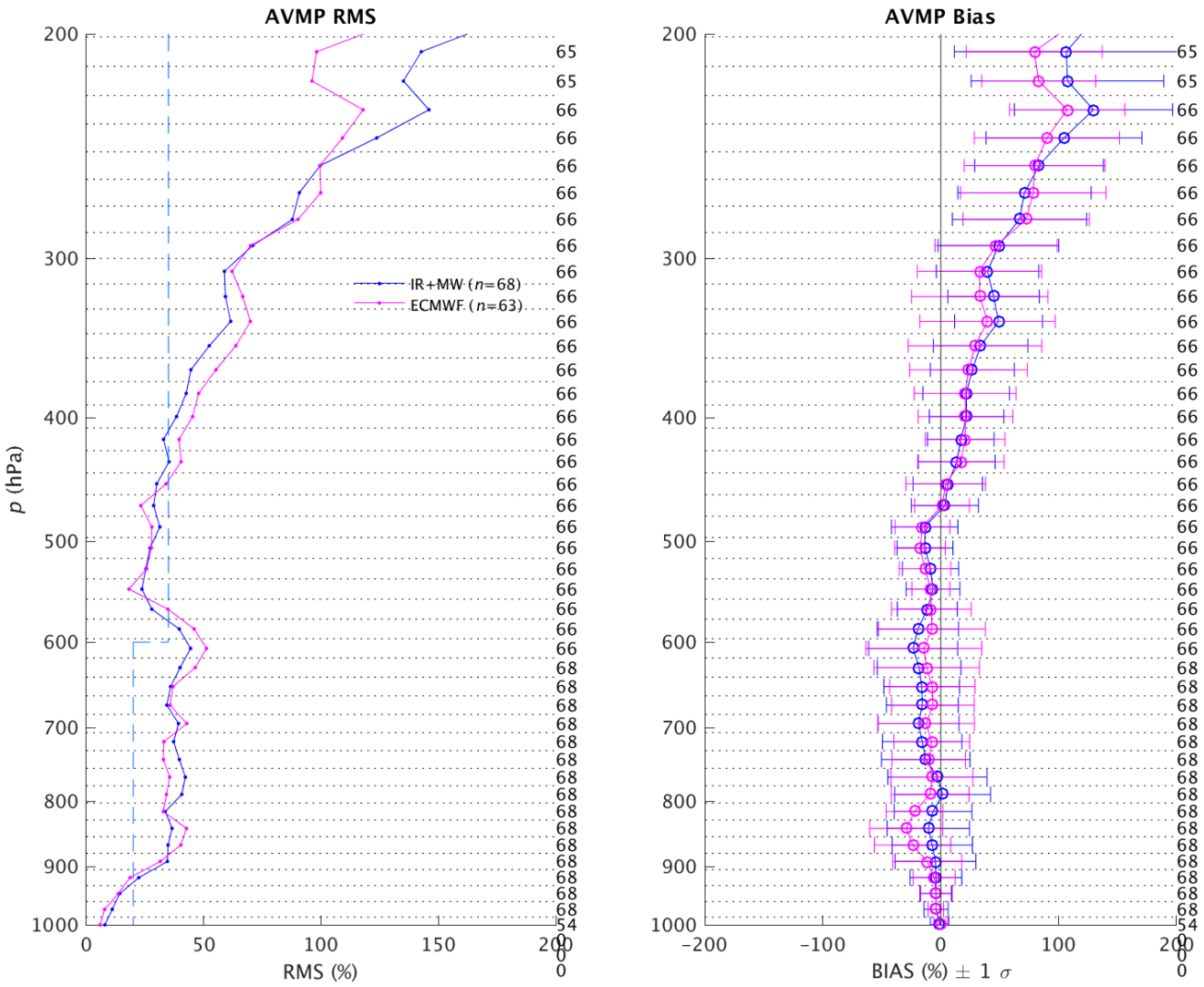


AVMP Statistical Summary (Accepted Cases)

2015 CalWater/ACAPEX RAOBs, 100 RTA Layers

Accepted FOR within 50 km radius

Launches 0–70 min prior to overpasses

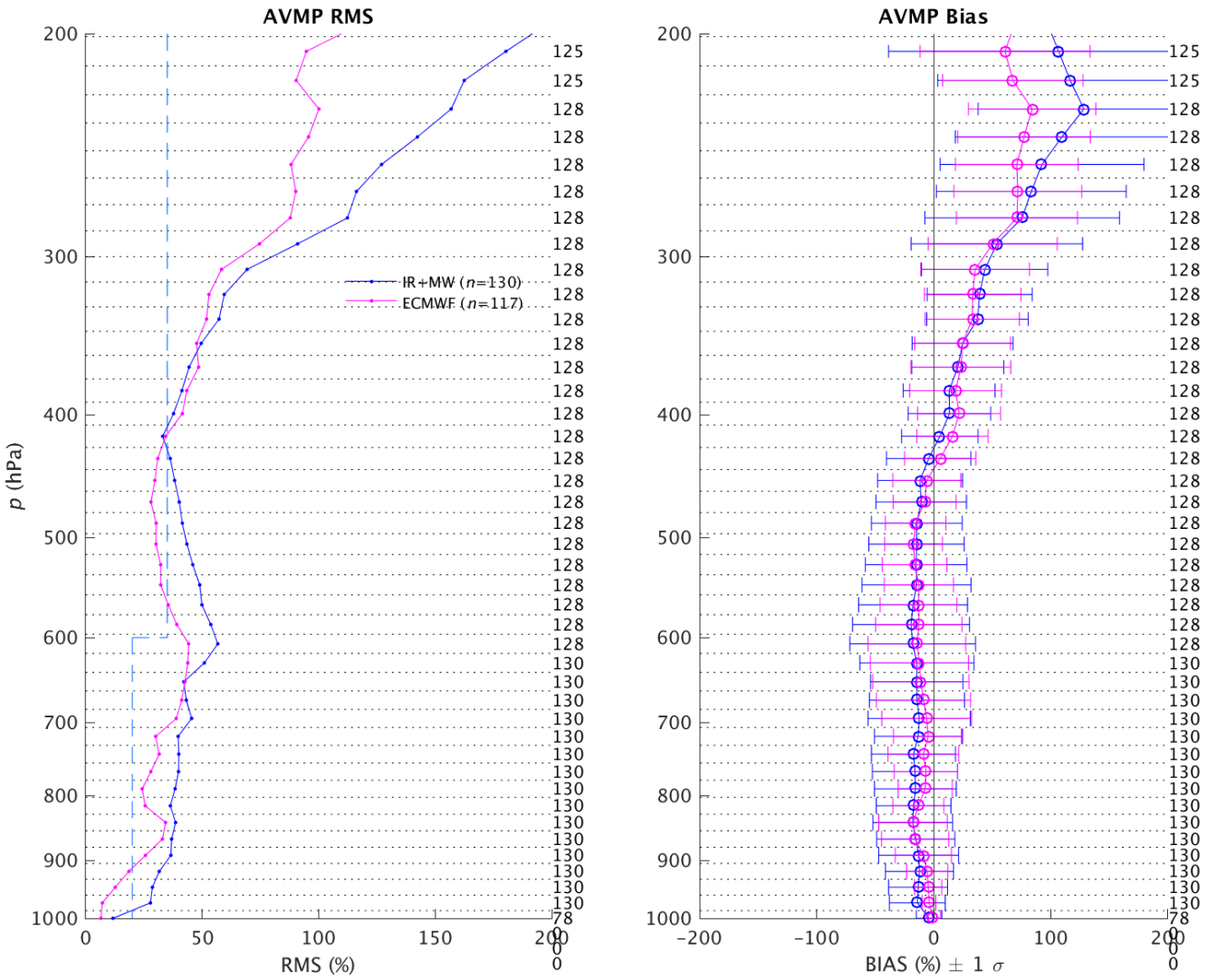


AVMP Statistical Summary (All Cases)

2015 CalWater/ACAPEX RAOBs, 100 RTA Layers

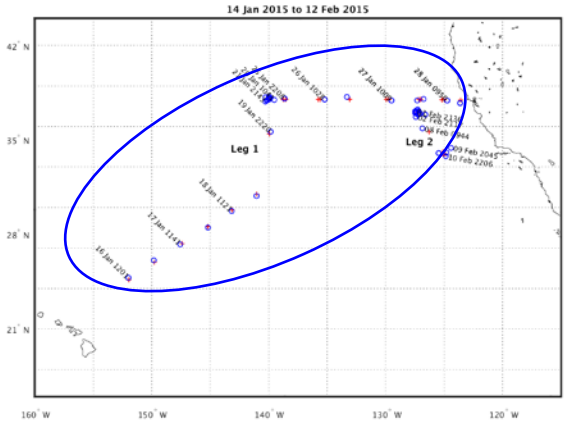
All FOR within 50 km radius

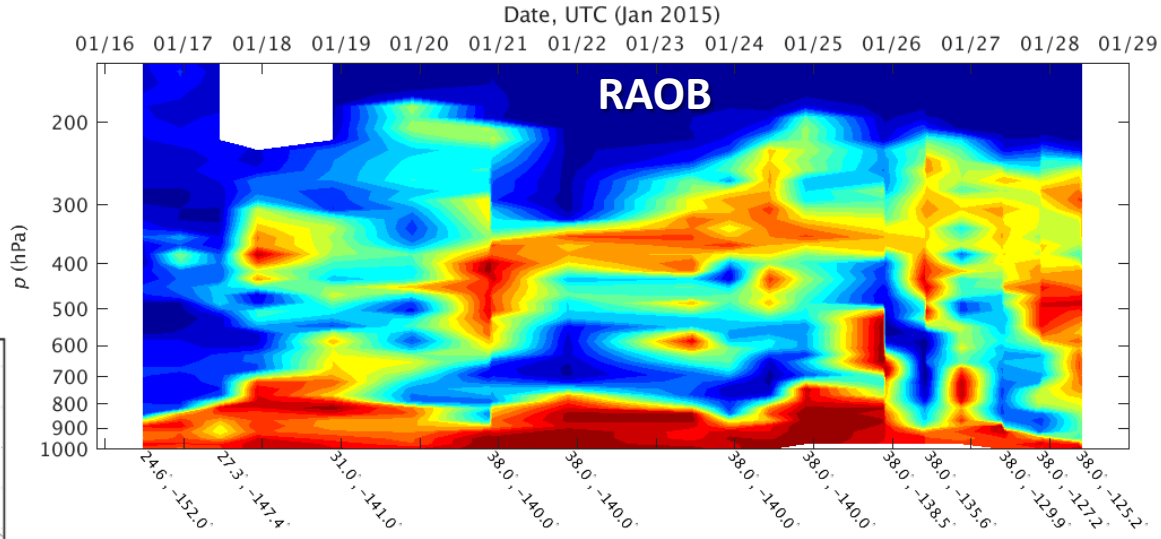
Launches 0–70 min prior to overpasses

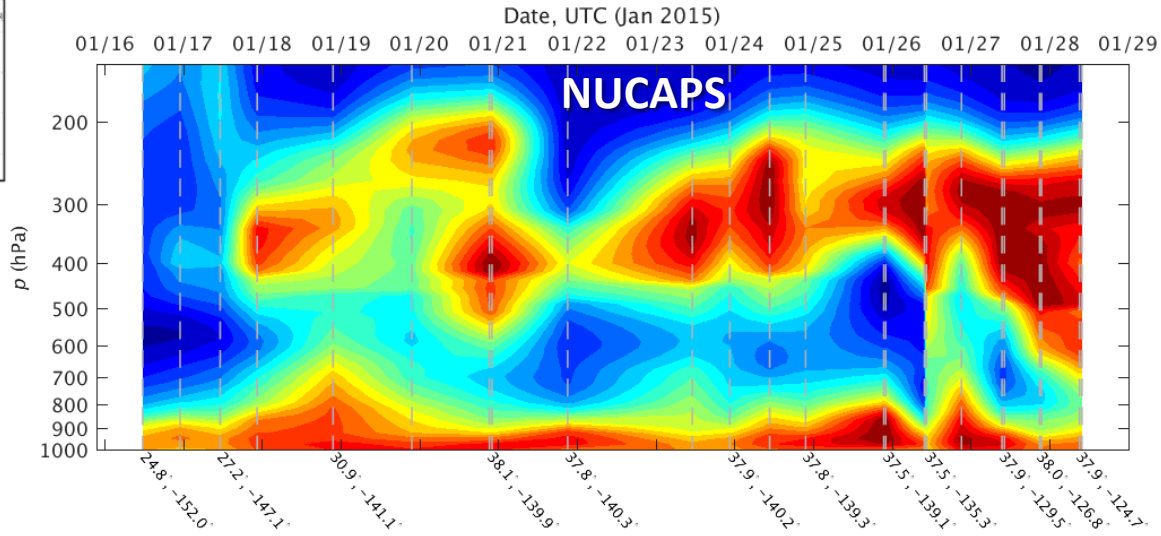


Temporal RH Cross-Section (Accepted Cases)

2015 CalWater/ACAPEX Leg 1

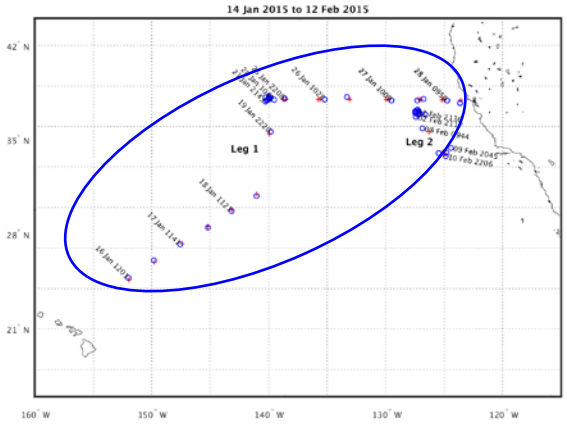


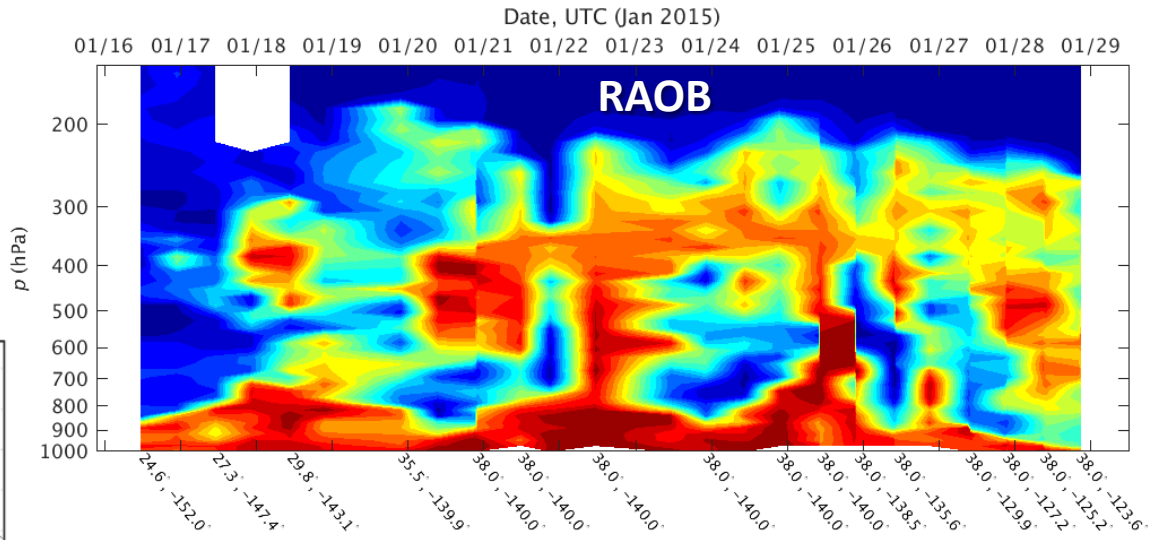


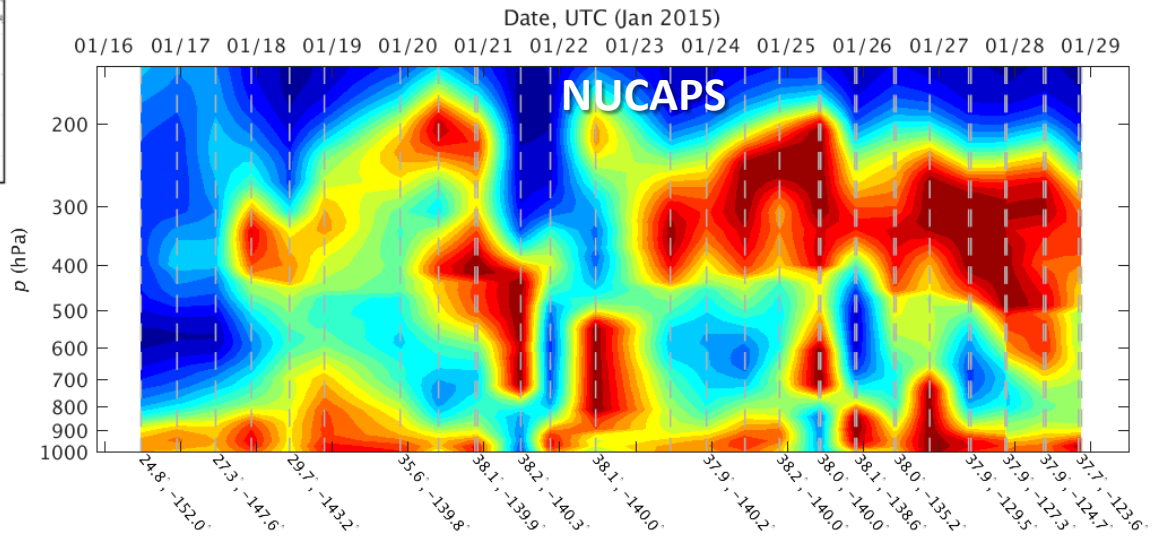


Temporal RH Cross-Section (All Cases)

2015 CalWater/ACAPEX Leg 1

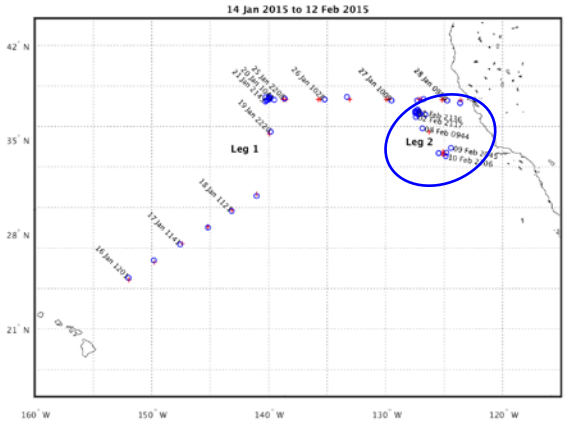


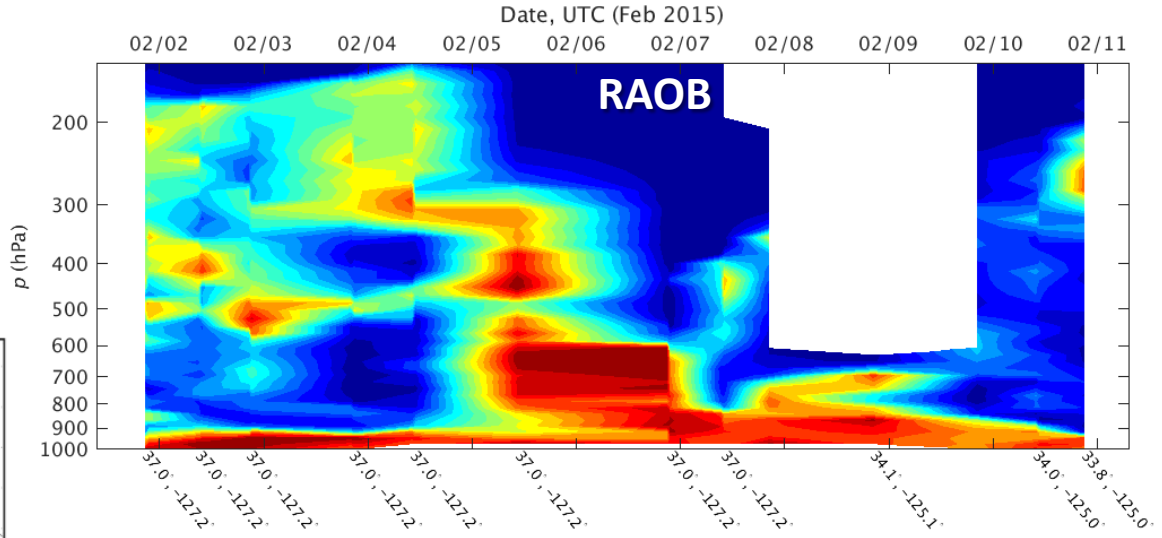


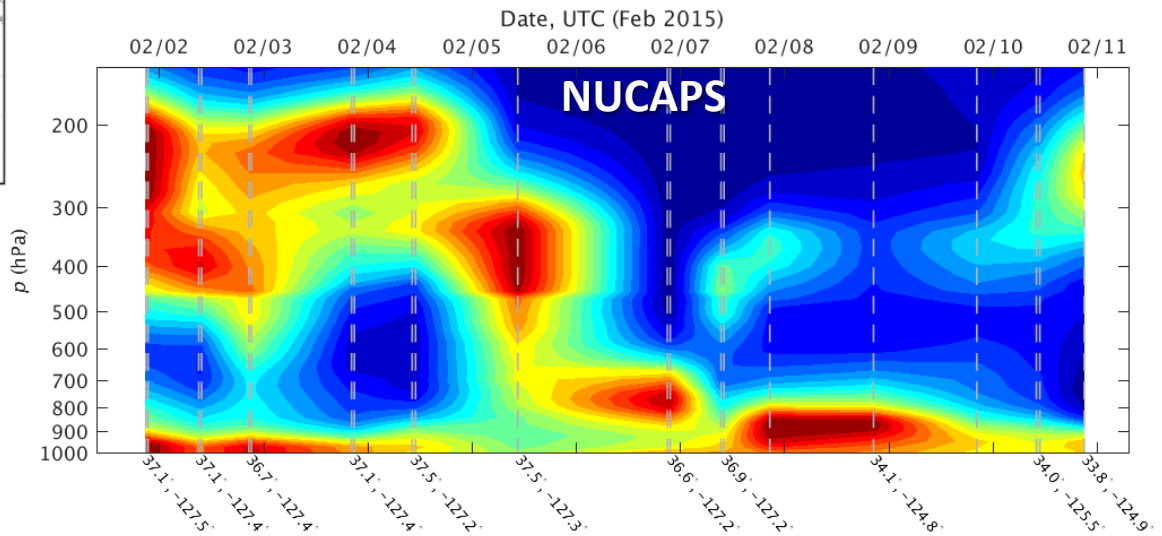


Temporal RH Cross-Section (Accepted Cases)

2015 CalWater/ACAPEX Leg 2

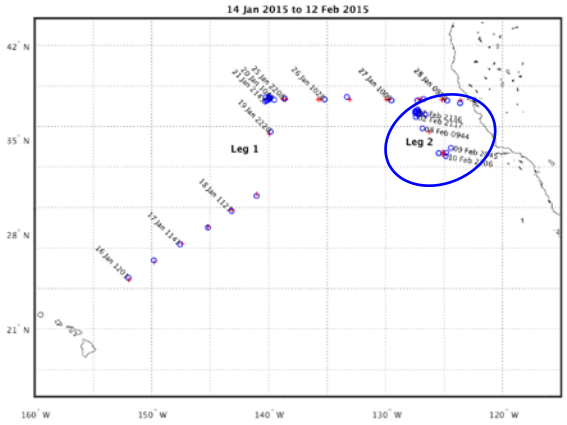


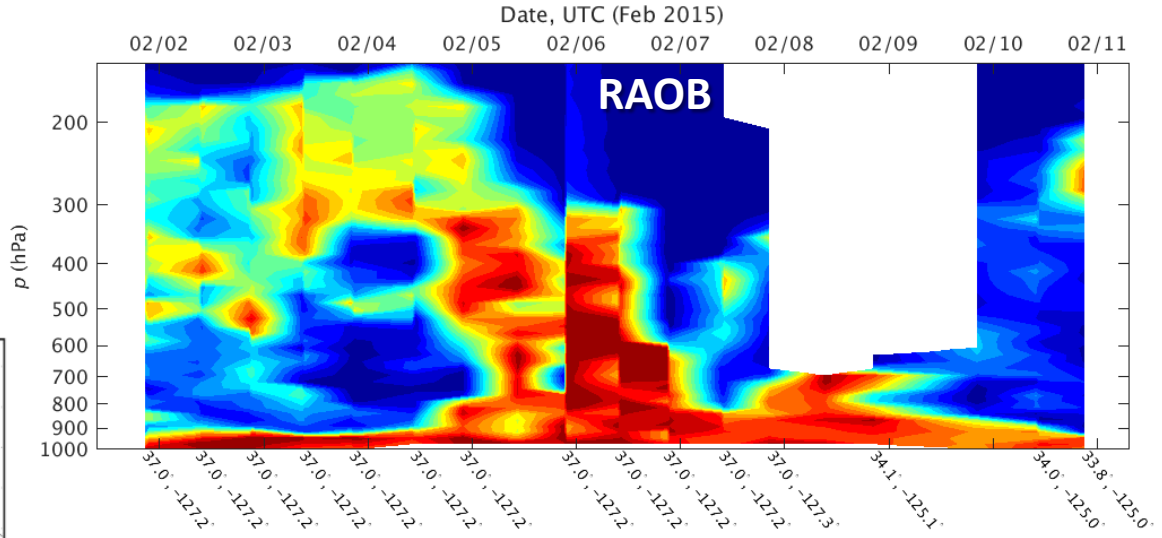


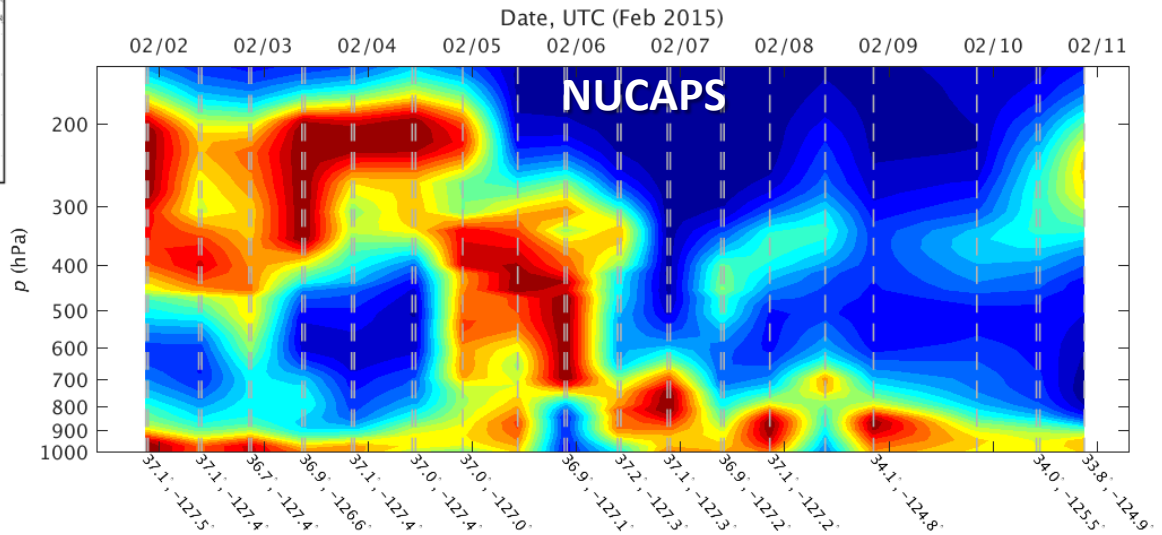


Temporal RH Cross-Section (All Cases)

2015 CalWater/ACAPEX Leg 2







Satellite Sounder Observations of Contrasting Tropospheric Moisture Transport Regimes

SUMMARY AND DISCUSSION

Summary and Discussion (1/2)

- This work has highlighted CrIS/ATMS sounder EDR performance based upon a unique collection of datasets obtained **under very different hydrometeorological conditions** associated with moisture transport mechanisms (advection and convection)
  - Statistical analyses of the SNPP NUCAPS retrievals (including cases rejected by the quality flag) versus independent dedicated RAOBs were found to be reasonably close to JPSS global performance specifications and ECMWF model output
  - In RH cross-sectional analyses, the **NUCAPS EDRs are shown to be capable of providing information about the distribution of tropospheric water vapor**, including mesoscale SALs and ARs, as well as synoptic scale Hadley subsidence cells and ITCZs

Summary and Discussion (2/2)

- Ocean cases are often considered "easy" within the satellite sounder community. However, these cases include atmospheric conditions that **pose difficulties for passive sounder retrievals**, including
  - Significant inversions associated with the SAL and subsidence
  - Tropical convection within the ITCZ
  - Heavy uniform cloud cover and precipitation associated with ARs
  - IR attenuation from Saharan dust aerosols
- This work has focused only on SNPP NUCAPS, but we expect similar performance for other satellite hyperspectral sounding systems
- Regarding **Atlantic Ocean SAL** and **Pacific Ocean AR** phenomena, it is our observation that, although they result from different underlying dynamics, these may be conceptually viewed as **inverses of one another** in terms of their non-local impact due to moisture transport
  - **SALs** are narrow layers of dry, warm air of desert origin that advect stabilizing "negative-moisture" over the ocean downstream
  - **ARs** are defined by narrow corridors or filaments of high water vapor content (e.g., *Neiman et al.* 2008; *Dacre et al.* 2015) of marine convective origin that advect "positive-moisture" over the continent downstream

Satellite Sounder Observations of Contrasting Tropospheric Moisture Transport Regimes

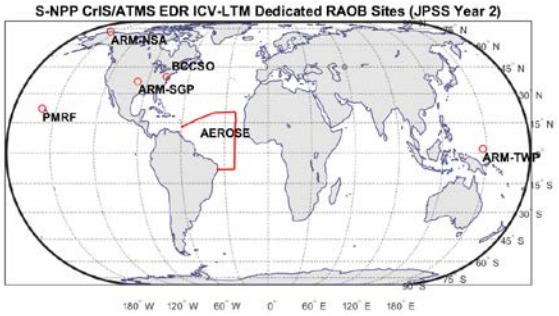
THANK YOU! QUESTIONS?

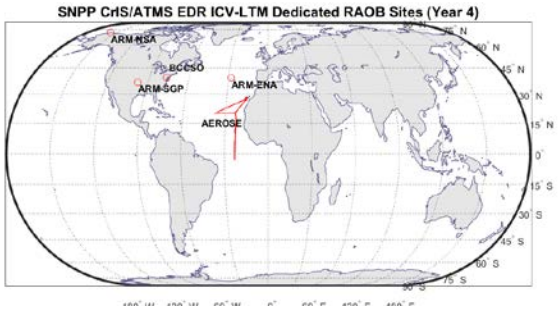
Satellite Sounder Observations of Contrasting Tropospheric Moisture Transport Regimes

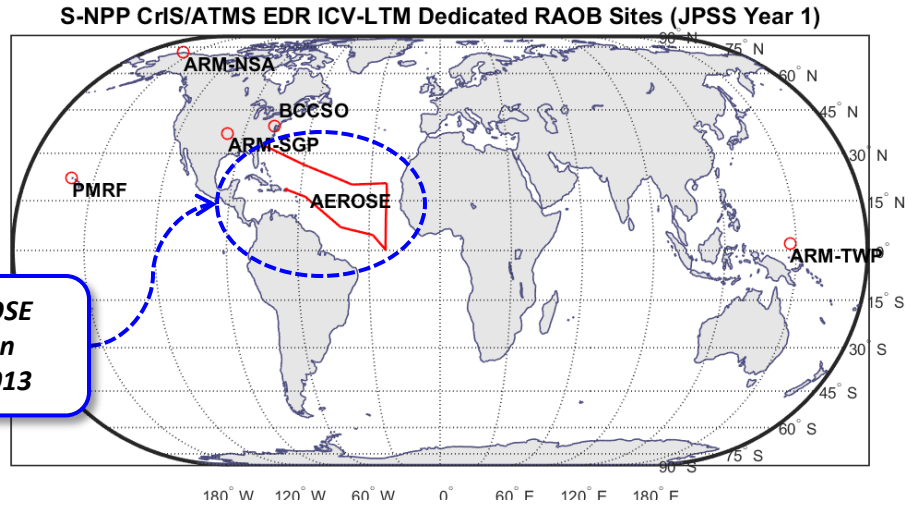
EXTRA SLIDES

JPSS SNPP Dedicated and Reference RAOBs

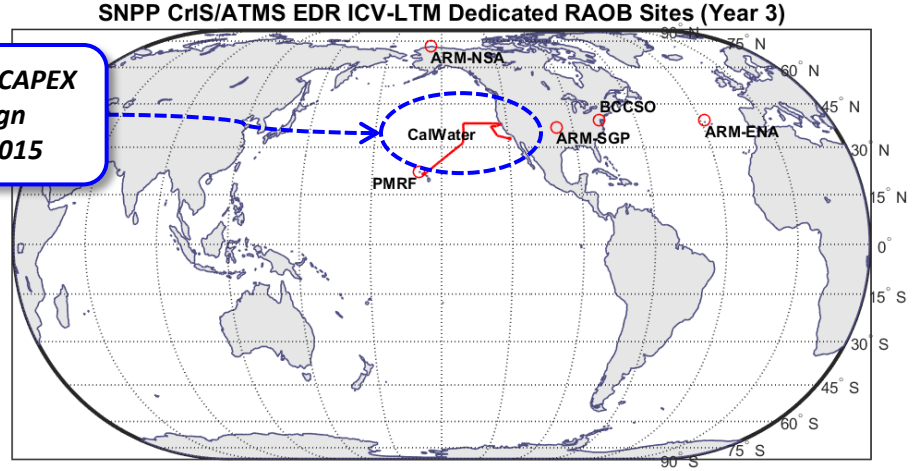
JPSS SNPP Dedicated Years 1–4 (2012-2016)





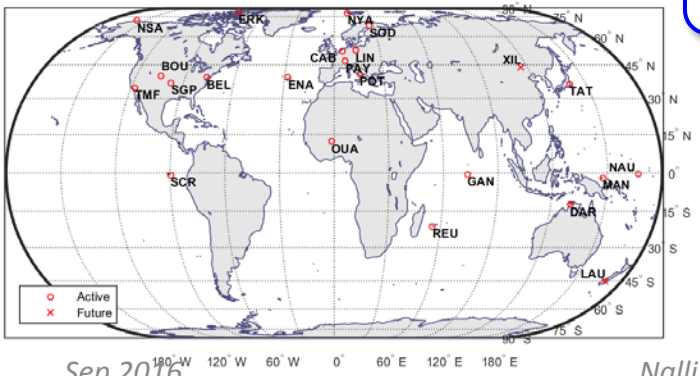


PNE/AEROSE Campaign Jan-Feb 2013



CalWater/ACAPEX Campaign Jan-Feb 2015

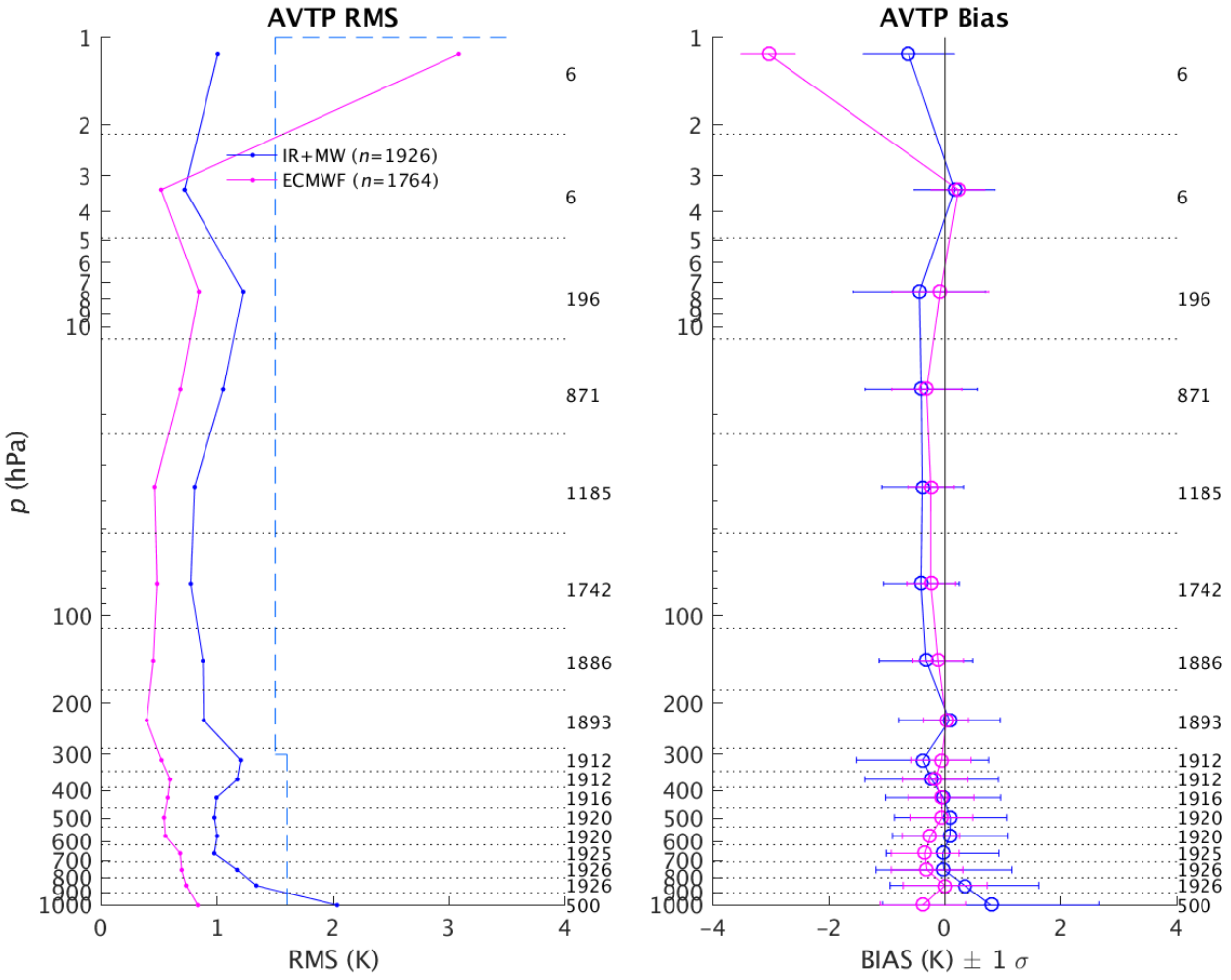
GRUAN Reference Sites



NUCAPS Offline (v1.5) AVTP and ECMWF Coarse-Layer Statistics
VALAR Dedicated/Reference RAOB Collocation Sample

IR+MW AVTP and ECMWF Versus RAOB

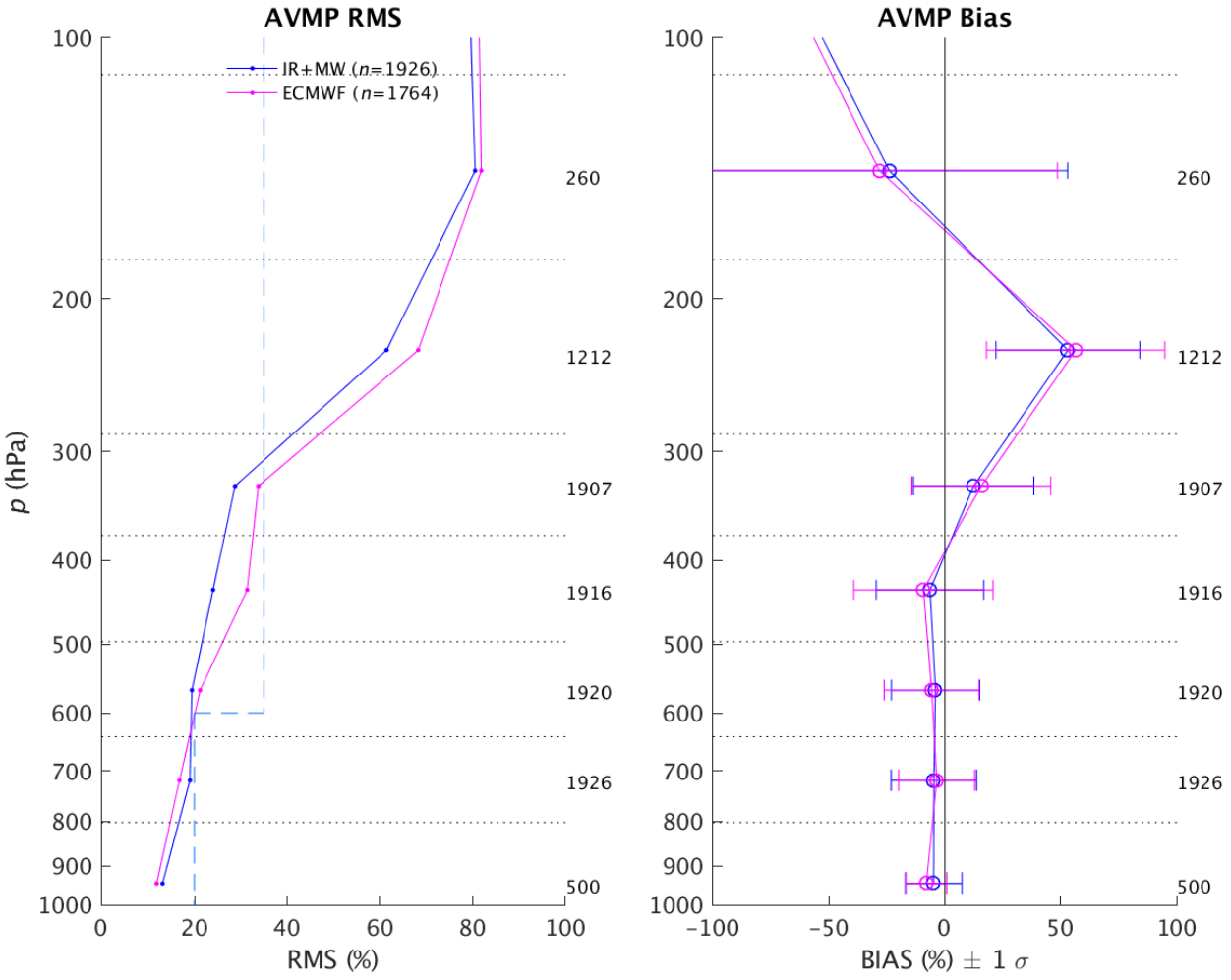
IR+MW Yield = 63.3%



NUCAPS Offline (v1.5) AVMP and ECMWF Coarse-Layer Statistics
VALAR Dedicated/Reference RAOB Collocation Sample

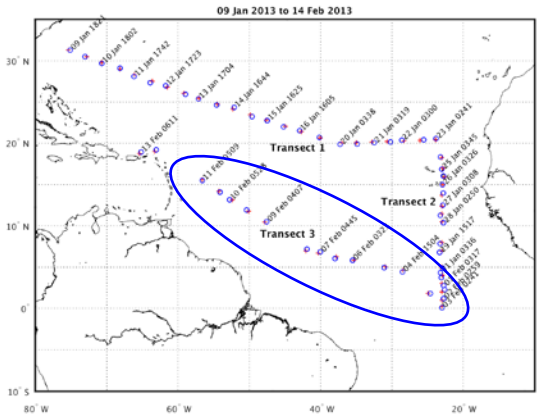
IR+MW AVMP and ECMWF Versus RAOB

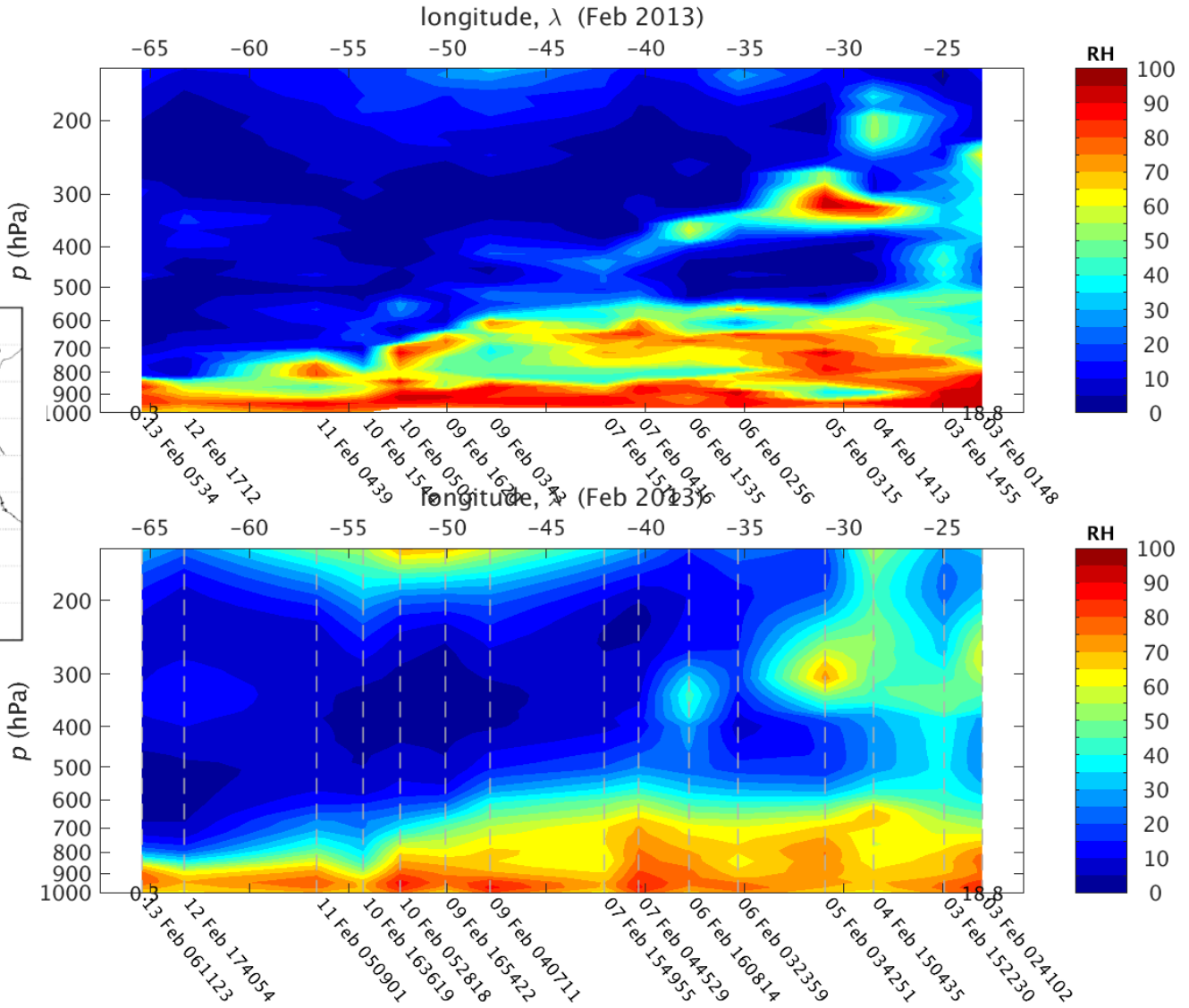
IR+MW Yield = 63.3%



Zonal RH Cross-Section (Accepted Cases)

2013 AEROSE SE-NW Transect 3





Zonal RH Cross-Section (All Cases)

2013 AEROSE SE-NW Transect 3